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SOME OF THE RELATIONS OF MAGNETITE AND HEMATITE.[1]

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INTRODUCTION.

With the exception of the titaniferous magnetites, comparatively little work has been done on polished surfaces of the iron ores. Lack of interest in them has been due chiefly to the fact that comparatively few points of economic importance which could have been settled by such examination have arisen. This, added to the difficulty of properly polishing them, and the necessity of having equipment which will furnish powerful illumination for examination at high magnifications, accounts for the investigators' preference to ores of other metals.

Examination of some forty polished sections of magnetite-hematite ores from widely scattered localities serves to suggest a series of problems concerning which little is known. The writer realizes that this article touches upon many points without presenting definite conclusions, but it is thought that the relationships observed are worthy of description.

THE EVIDENCE OF SOLID SOLUTION IN THE SERIES Fe_2O_3—Fe_3O_4.

One of the first things to be considered in the study of the relations of magnetite and hematite is the evidence of the exist-

[1] Communication from the Laboratory of Economic Geology of Massachusetts Institute of Technology, Cambridge, Mass.

ence of solid solutions intermediate in composition. Several articles have appeared recently, in which the conclusion is reached that solid solutions in the system Fe_2O_3 — Fe_3O_4 exist in nature.[2] The following quotations illustrate the confidence of the writers:

"Natural oxides of iron intermediate in composition between Fe_2O_3 and Fe_3O_4 are much more common than is generally supposed."[3]

"These martites are found in fact to be both pseudomorph and solid solution at the same time."[4]

"The natural iron oxide minerals are similar to the artificial in being in many cases solid solution of Fe_3O_4 in Fe_2O_3."[5]

"Some of these (natural) oxides are true homogeneous solid solutions."[6]

The writers of these articles admit that two explanations would account for the presence of FeO in the specimens which they examined. It could be present either in solid solution in the hematite or in admixed magnetite (assuming no ferrous silicate or carbonate present). The evidence upon which the former alternative was chosen is based upon (1) the apparent microscopic and magnetic homogeneity of the material and (2) in the case of certain ores, notably that from Juragua, Cuba, an apparent peculiarity in their magnetic behavior.

In regard to the microscopic homogeneity of the specimens examined at the Geophysical Laboratory, the writer can find in the descriptions of the methods of research no evidence of any microscopic examination of polished surfaces having been made. In addition to many other iron ores, the writer has examined polished surfaces of ores from the localities which are considered by Sosman and Hostetter as being the best examples of solid solution. In the cases of the ores from Daiquiri and Juragua, the writer was fortunate enough to secure the same

[2] Sosman, R. B., and Hostetter, J. C., "The Ferrous Iron Content and Magnetic Susceptibility of Some Artificial and Natural Oxides of Iron," *Trans. Am. Inst. Min. Eng.*, Vol. 58, 1918, pp. 409–433. "Zonal Growth in Hematite and its Bearing on the Origin of Certain Iron Ores," *op. cit.*, pp. 434–444.

[3] *Op. cit.*, p. 409.

[4] *Op. cit.*, p. 431.

[5] *Op. cit.*, p. 433.

[6] *Op. cit.*, p. 434.

specimens from which they obtained their material. Other specimens examined interesting in this connection include martite from Twin Peaks, Utah, specular hematite from the Isle of Elba; Dognacska, Hungary; East Mesabi district, Minn., and others. In all these cases of "magnetic hematites" residual magnetite was found in various degrees of replacement by the hematite (see later descriptions and figures). In some cases the lack of homogeneity can be seen with the naked eye. Purplish spots scattered over a surface of hematite (not necessarily polished) indicate magnetite. In other instances, however, replacement has gone so far that the residual magnetite can be seen only through high power lenses.

As for the reported magnetic homogeneity of certain hematites carying FeO, doubt arises as to the efficacy of the methods of separation attempted and as to whether or not the ores were ground finely enough for a true magnetic separation. It is well known to those interested in the possibilities of magnetic separation of fine-grained intergrowths of magnetite and non-magnetic gangue minerals, that a clean separation in the dry state is almost impossible. The entrainment of the non-magnetic material with the magnetite results in very poor fractionation. At any rate, to separate the hematite from the magnetite in the Juragua ore, the diameter of the particles should be of the order 10^{-3} to 10^{-4} millimeters. Any "magnetic fractions" of coarser material simply represent the separation of particles having different proportions of magnetite and hematite. Plate XI., *a*, shows that hematite areas with a diameter less than .001 millimeter run through the magnetite. While Sosman and Hostetter do not state the size of the product which they fractionated magnetically, one gathers from the precautions which they took to prevent oxidation during grinding, that it could not have been finer than 100-mesh (maximum diameter .14 mm.).[7] Thus assuming the best possible technique in separation, the three magnetic fractions of the Juragua ore simply represent three aggregates of particles, each being a mixture of magnetite and hematite in different pro-

[7] *Op. cit.*, p. 421.

portions, for a particle .14 millimeters in diameter would contain millions of particles of the size necessary for separation of the hematite magnetite combinations visible under the microscope.

In the case of the Juragua ore, a peculiar bit of evidence is cited as favoring its being a solid solution rather than a mixture of magnetite and hematite. Various artificial mixtures of crushed magnetite and quartz were prepared and their FeO content plotted against their magnetic attraction on a logarithmic scale. It is then assumed that points similarly plotted for any natural mixture or solid solution of Fe_2O_3 and Fe_3O_4 should be on or below that curve. Three "magnetic fractions" of the Juragua ore were obtained, and their FeO content and magnetic attraction obtained and points plotted as in the case of the artificial quartz magnetite mixtures. It is found that the three points representing the three fractions lie below the quartz-magnetite mixture line, but at different distances from it, the one lowest in FeO being most distant. (See Fig. 24.) This is found to be true of points representing magnetic fractions of ores from other localities. Sosman and Hostetter say of the Juragua ores:

"It is difficult to reconcile this graded deviation of the successive fractions away from the mixture line with Lindgren and Ross's theory of the origin of the South Cuban ores, according to which the ore was originally magnetite, which has been oxidized by oxygen from the surface. If the ore were simply a mixture of hematite and unoxidized magnetite, all of the fractions should be on the mixture line or deviate from it by a constant amount."[8]

Here as elsewhere the writers evidently have failed to take into account the fact that their points are plotted on a logarithmic scale. If instead of a logarithmic scale, direct plotting be used, the curve connecting the points representing the Juragua ore is practically parallel to the quartz-magnetite mixture curve, in fact, approaches it slightly with lowering of the FeO content instead of deviating from it. (See Fig. 24.) This, of course, is to be expected, for if the magnetic susceptibility is proportional to the FeO content the curves should meet at the origin. However,

[8] *Op. cit.*, pp. 429–430.

even though the graded deviation with the lowering of the FeO disappears when the Juragua and quartz-magnetite mixture curves are plotted on normal scale, there is still to be explained the fact that the points for the Juragua ores do not lie on the quartz mixture curve. In each case they show a magnetic attraction equal to that of a quartz magnetite mixture having an FeO

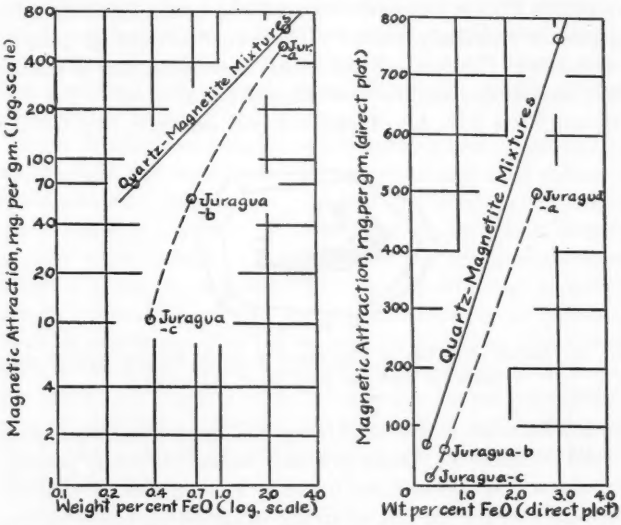


FIG. 24. Left-hand diagram; part of Sosman and Hostetter's curves showing relation of quartz magnetite mixture line and curve through points representing Juragua ore. True relation of curves obscured because of being plotted on logarithmic scale. Right-hand diagram; same data as on other diagram, directly plotted. True relations of curves are thus shown.

content lower by about .2 to .4 per cent. Before any significance as an argument for solid solution is attached to this small excess of FeO over the amount necessary to produce the same attraction in magnetite, the absence of ferrous silicates, carbonates or other salts should be proved. Therefore one is left with the feeling that there is nothing in these magnetic experiments to forbid the ore being just what it appears to be under the microscope, a mix-

ture of magnetite, hematite and gangue, with possibly some hydrated oxides, not to mention a small amount of pyrite and chalcopyrite. (Plates XI., *a* and XII., *a*.)

In the case of the Isle of Elba crystal it is not clear why Sosman and Hostetter decide that the FeO content varies in such a manner that the crystal as a whole may be called "zoned" in respect to FeO in somewhat the same way as the lime-soda feldspars are frequently zoned.[9] The writer selected at random seven Isle of Elba crystals and crystal aggregates, and on sawing them in sections found residual magnetite in all cases. (See Fig. 25, and Plate XII., *b*.) It was not even necessary to polish the

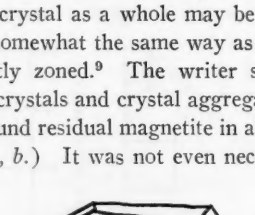


FIG. 25. Sketch of an Isle of Elba hematite crystal showing residual magnetite (in black) on basal plane. (To scale.)

surface to see the magnetite in most of them. To apply the terms "solid solution" or "zonal growth" without definitely proving the absence of admixed magnetite by examination of polished surfaces is to run the risk of giving an altogether erroneous impression of such mixtures.

Similarly with the martites careful microscopic work should be done before their FeO content is assigned to solid solution. The writer has found various hematites to be "martites" in the sense that they are more or less completely replaced magnetite. One large octahedron, two inches on the edge, from Twin Peaks, Utah, was examined. It showed distinctly, in polished section, rather uniformly scattered patches of residual magnetite.

One of the most certain criteria of the existence of solid solutions between artificial Fe_2O_3 and Fe_3O_4 seems to be the optical

[9] *Op. cit.*, p. 440.

tests.[10] One wonders why this test was not used in establishing the existence of the solid solutions in nature since it was successful with the artificial products.

Thus the published evidence of the existence of these natural products intermediate between magnetite and hematite is altogether unsatisfactory to the geologist. The writer has no objection to the idea of there being such solid solutions, but maintains that if conclusions are to be drawn which depend upon the assumption that a mineral is homogeneous, if it be an opaque mineral, a polished surface should be examined under the high power lenses of the metallographic microscope.

Such examination of the magnetite-hematite ores reveals things which might well be explained by the existence of solid solutions intermediate between the two minerals. Polished surfaces show color variations of both of the minerals which are distinct enough to show in photographs. Such surfaces of some minerals show different colors by reflected light, varying with the crystallographic orientation of the section. Covellite is an example. Such an explanation does not account for all of the color variations noted in the different hematites and magnetites, however, for in one case it was possible to observe a distinct color difference between two magnetite crystals in contact, and of the same orientation (proved by the parallelism of replacements along parting planes).

In certain specimens, the amount of magnetite seen under the microscope seems to be too small to account for their magnetic properties. Two specimens in Professor Lindgren's collection are of this type, one from the Grängesberg district, Sweden, and the other from a Lake Superior locality. In such instances the type of quantitative work done by the Geophysical Laboratory, combined with microscopic research would be of value, because such cases are most suggestive of the existence of solid solutions.

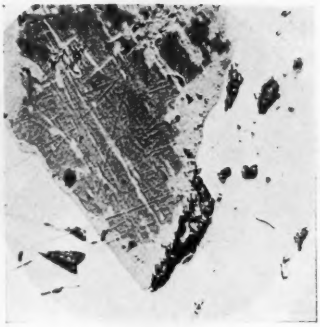
On etching certain apparently homogeneous magnetite grains in hot HCl and $SnCl_2$, peculiar zonal structures are brought out

[10] Sosman, R. B., and Hostetter, J. C., "The Oxides of Iron I; Solid Solution in the System Fe_2O_3–Fe_3O_4," *Jour. Am. Chem. Soc.*, Vol. 38, No. 4, 1916, p. 829.

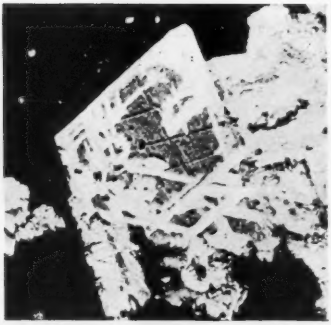
which are similar in appearance to those seen in the plagioclase feldspars (Plate XII., *c*). One of the Isle of Elba crystals showed a similar appearing zonal structure in the residual magnetite which did not require etching to be made visible. Replacement by hematite tended to follow the zonal directions in this case. It is noticed that these zones are rounded in some cases, and polyhedral in others. Plate XII., *c*, looks as though the crystal developed as an octahedron with its edges truncated by a dodecahedron. This zoning is apparently due to changes during the growth of the crystal. Under the highest magnification available the structure is seen to be brought out by the formation of many little solution pits. Whether it be due to changes in density, differences in pore space, or to variations in composition due to the properties of solid solutions, the writer is not prepared to state. The rounded outlines seen in some crystals suggest that variations in composition is the correct explanation. Certain it is that it is not to be explained as a mere mechanical mixture of hematite and magnetite, as seems to be the case of many of the Isle of Elba crystals. Whatever may be the cause of this zonal effect, it has the appearance which would be expected if it were due to zonal growth in a solid solution series.

Again, certain constituents tentatively called hematite are affected by etching reagents differently from well crystallized specular hematite. Both limonite and magnetite are found to be easily etched by a solution of $SnCl_2$ in dilute HCl, while good specular hematite is not. A mineral looking like hematite found replacing magnetite is found to be slightly etched by this solution. This suggests either a hydrous oxide differing from limonite in appearance, or a solid solution of Fe_3O_4 and Fe_2O_3. More work is necessary to state the situation with any greater certainty. The microscopic examination by Merwin[11] of the Twin Peaks, Utah, martite in which it is found to be optically similar to turgite, is suggestive of the nature of some such replacement products. In the following description of the relationships of the oxides of

[11] Sosman, R. B., and Hostetter, J. C., "The Ferrous Iron Content and Magnetic Susceptibility of Some Artificial and Natural Oxides of Iron," *Trans. Am. Inst. Min. Eng.*, Vol. 58, 1918, p. 431.



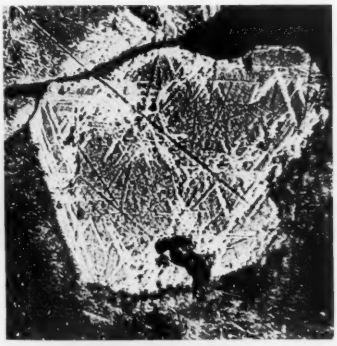
a.



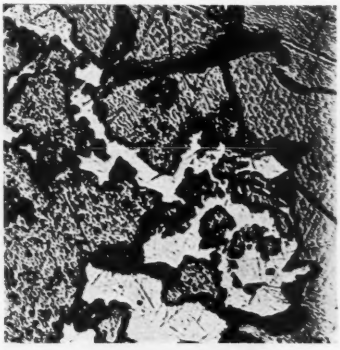
b.

FIG. *a*. Dark wedge-shaped area magnetite. Greater part of field is hematite, almost same age as magnetite. Magnetite altering to material having properties of hematite, but of slightly different color from primary hematite. Lindgren's Juragua, Cuba; No. 12. × 790.

FIG. b. Octahedron of magnetite showing replacement along octahedral planes by hematite. Dark surrounding material is quartz. Grout's Mesabi specimen, No. M-256. × 960.



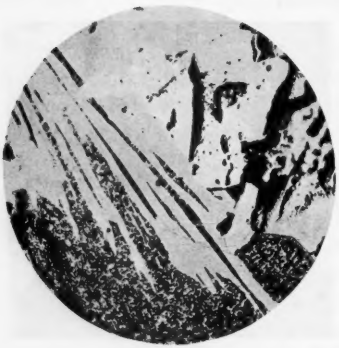
c.



d.

FIG. *c*. Like Plate XII., d, magnetite grain surrounded and cut by limonite and being replaced around the borders by hematite (white) along octahedral planes. Lindgren's Daiquiri, Cuba; No. 10. × 720.

FIG. *d*. Replacement of magnetite (dark gray with rough surface) by hematite (white) in irregular veinlets. Black borders along hematite veinlets developed by etching. Lindgren's Norberg, Sweden, specimen. × 455.



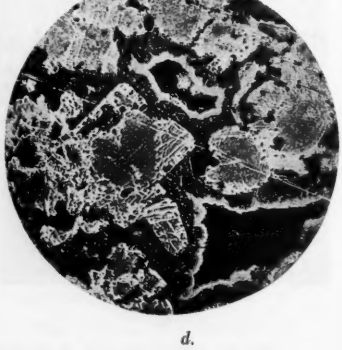
a.

b.

FIG. *a*. Interpenetrating bladed hematite (light) and magnetite (dark), of about the same age. Magnetite largely altered to hematite of second generation. Lindgren's Juragua, Cuba; No. 12. × 327.

FIG. *b*. Part of magnetite hematite areas shown in Fig. 25. Magnetite (dark) replaced by hematite (light). Lattice work in magnetite is hematite replacing the magnetite along its octahedral planes. Isle of Elba specular hematite crystals. × 425.

c.



d.

FIG. *c*. Zonal structure developed in magnetite by etching with hot solution of $SnCl_2$ in dilute HCl. Lindgren's Daiquiri, Cuba; No. 23. × 220.

FIG. *d*. Magnetite crystals (gray) with partial replacement around outside of grains by network of hematite (white). Dark gray material around the magnetite is limonite. Lindgren's Daiquiri, No. 10. × 312.

iron, it is realized that the terms magnetite, hematite and limonite may be used to designate compounds of slightly variable composition or material of varying degrees of hydration.

THE RELATIONS OF MAGNETITE AND HEMATITE.

The relations of magnetite and hematite observed in the present work may be classified as follows:

- I. Both mineral hypogene
  - 1. Nearly contemporaneous.
    - *a*. Interpenetrating relations.
    - *b*. Smooth rounded contacts.
  - 2. Replacements of magnetite by hematite.
    - *a*. Along crystallographic directions of the magnetite.
    - *b*. In irregular veinlets.
  - 3. Replacement of hematite by magnetite.
- II. Magnetite hypogene, hematite supergene.

A description of these various classes will be taken up in the above order.

Both Minerals Hypogene.—Hematite and magnetite appear in intergrowths of a type which are best explained as being formed by the almost simultaneous crystallization of the two minerals. One such intergrowth is the interpenetration of the magnetite with bladed or micaceous hematite. In this case the habit of the hematite evidently has controlled the form assumed by the intergrowth. Such an occurrence is well illustrated by Plate XII., *a*. The specimen is from Juragua, Cuba. The magnetite has since been more or less completely replaced by what is apparently hematite of a second generation.

Another type of nearly simultaneous formation of the two minerals is seen in certain ores where the contacts of the two minerals are rather smooth curves. Such relations were noted in certain Swedish ores. No veinlets of one mineral in the other were found in these specimens.

The sharp contacts between the magnetite and hematite in these cases of nearly contemporaneous formation are not those which one would picture as being characteristic of minerals capable of forming solid solutions. However, the dissociation pressure

curves of Hostetter and Sosman[12] show that small changes in oxygen pressure are capable of changing the product from predominantly magnetite to predominantly hematite. Thus a small change of pressure during comparatively rapid crystallization, would account for the relations described.

The most common type noted of hypogene intergrowth of the oxides, however, is a replacement of magnetite by hematite. Frequently this replacement takes place along the octahedral planes of the magnetite. One case was noted where the replacement had a tendency to follow a zoning of the magnetite in another direction, besides being developed along the octahedral planes. Plate XI., *b*, shows a section of an octahedron of magnetite being replaced by hematite along those planes. One of the best examples of this process is found in the specular hematite crystals from the Isle of Elba. As mentioned above, crystals of this material were selected at random, cut and polished and found in all cases to have started as a replacement of magnetite. Further deposition of Fe_2O_3 on the more or less completely replaced magnetite crystals resulted in the formation of the well-known Elba hematite crystals. In general the residual areas of unreplaced magnetite are more abundant near the point of attachment of the crystal, although considerable variation was noted in this respect. Fig. 25 shows the distribution of the partially replaced magnetite on a basal plane of one of the specimens. Plate XII., *b*, is a photomicrograph of a part of the area marked magnetite in Fig. 25. The great complexity of the residual magnetite areas is apparent. An interesting crystallographic study would be to determine the relation of the elements of the hematite crystal to those of the magnetite crystal. In the hasty investigation of this point, the writer has not determined what the relationship is between the two crystals, but that a crystallographic parallelism exists in some cases is certain. In the crystal figured above were found good examples of the varying colors of magnetite which have been referred to as suggesting the possibility of natural solid solutions in the Fe_2O_3—Fe_3O_4 series.

[12] *Op. cit.*, p. 410.

This replacement of magnetite along the octahedral planes is suggestive of the magnetite ilmenite intergrowths. Those who have studied the latter, however, do not seem to regard them as replacements of the magnetite, but as simultaneous crystallizations. In the hematite-magnetite relations there are all degrees of replacement. Sections of magnetite may be seen with a few stringers of hematite along the parting planes, and hematite may be seen with scattered polyhedral remnants of magnetite. In the published figures of ilmenite magnetite intergrowths, the relative proportions of the two minerals are much more constant. Apparently the two cases, although resembling each other in appearance in many instances, are genetically different.

A few hypogene replacements of magnetite by irregular stringers of hematite were noted. Plate XI., *d*, shows such a case. The reason why this replacement does not follow the octahedral planes of the magnetite is not apparent, for in this particular magnetite the parting planes are well developed.

As previously stated, the "hematite" found to replace the magnetite in some specimens is different in its behavior from good specular hematite such as Isle of Elba material. For instance, Plates XI., *a* and XII., *a*, show Juragua ore where there has apparently been an almost simultaneous deposition of magnetite and hematite. Later, partial replacement of the magnetite has taken place, by material having the appearance of hematite. The boundaries between this second generation of hematite, if it be hematite, and the primary hematite, are distinct, the later material being of a very slightly different color.[13] This difference may be due to any of several causes: (1) The secondary material may be a hydrated oxide much lighter in color than hitherto described; (2) there may be in it many residual areas of magnetite of sub-microscopic size which may serve to give the color difference; (3) it may be a solid solution of magnetite

[13] It should be kept in mind that these color differences are often very slight. Important subdivisions in Murdoch's "Microscopical Determination of the Opaque Minerals," John Wiley & Sons, 1916, are based upon distinctions between grayish white, purplish white, creamy white, bluish white and galena white.

and hematite. The fact that the material is darkened by $SnCl_2$ in dilute HCl solution does not help in deciding what it is, as both magnetite and the hydrous oxides of iron are attacked by the same reagent.

Only a few specimens showing the replacement of hematite by magnetite were examined. One specimen from Juragua consists of micaceous magnetite, probably a pseudomorph after specular hematite. The formation of magnetite from other iron minerals during contact and regional metamorphism is a common process, and the minerographic study of selected specimens showing a gradation between the original material and the resultant magnetite rock should be interesting.

Magnetite Hypogene, Hematite Supergene.—The origin of the hematite of the iron ore deposits in the vicinity of Daiquiri, Cuba, has been the subject of some discussion.[14] No one disputed that the hematite is of later age than the magnetite. Lindgren and Ross held that, because of the abundance of scaly hematite near the surface and its scarcity in depth, it is the result of surface oxidation. Roesler and Singewald take the viewpoint that the "specular" type of hematite is a hypogene replacement of the magnetite. Microscopic study reveals that there is hematite in these deposits which was nearly contemporaneous with the magnetite (Plate XII., *a*). However, relations are found indicating that hematite of the same appearance as that formed by hypogene deposition is formed in these Cuban ores by supergene processes. In polished sections of bluish black specular hematite ore pyrite is seen in various stages of replacement by limonite. Along the borders of the limonite patches, around the

[14] Lindgren, W., and Ross, C. P., "The Iron Deposits of Daiquiri, Cuba," *Trans. Am. Inst. Min. Eng.*, Vol. 53, 1916, pp. 40–59.

Singewald, J. T., Jr., and Miller, B. L. "The Genesis and Relations of the Daiquiri and Firmeza Iron-Ore Deposits, Cuba," *Trans. Am. Inst. Min. Eng.*, Vol. 53, 1916, pp. 64–74.

Kemp, J. F., "The Geology of the Iron Ore Deposits In and Near Daiquiri, Cuba," *Trans. Am. Inst. Min. Eng.*, Vol. 53, 1916, pp. 3–38.

Roesler, M., "Iron-Ore Deposits of the Firmeza District," *Trans. Am. Inst. Min. Eng.*, Vol. 56, 1917, pp. 77–127. See especially discussion following Roesler's paper and in *Bull. Am. Inst. Min. Eng.*, May, 1916, pp. 886–893.

peripheries and in along the octahedral planes of the magnetite, thin plates of hematite, many less than .001 millimeter in thickness, are seen to reach up into the magnetite. Plates XII., *d*, and XI., *c*.) The bordering of the limonite patches by magnetite altering to hematite is common throughout several sections, suggesting that the same processes which changed the pyrite to limonite have caused the magnetite to alter to hematite. This is in accord with the observations of Lindgren and Ross who regard the relation of the distribution of the hematite to the surface as furnishing "an increased probability that descending surface waters effected this work" (*i. e.*, the replacement of magnetite by hematite).

The most notable case of the supergene alteration of magnetite known to the writer is the formation of the ore-bodies on the Mesabi iron range. Below the zone of oxidation, the iron formation has in many places a large proportion of magnetite.[15] Ore-bodies consisting of soft hematite and hydrous oxides are formed in this iron formation by the action of surface waters. A study of a few specimens from the vicinity of the ore-bodies, where the oxidation effects may be observed on the still hard material, indicates that in this case the magnetite is changed to limonite rather than to hematite by surface waters. In specimens where magnetite and presumably hypogene hematite are both present, magnetite seems to have changed over to limonite much more readily than the hematite. Areas of magnetite are seen badly altered to limonite, side by side with comparatively fresh hematite.

It is hoped that the continuation of this study of the iron oxides will serve to clear up some of the many points untouched or left uncertain in the present work. The study is not a simple one, however, as the history of the iron ore deposits is in many cases as complex as the history of deposits of other metals. The case of the deposits near Daiquiri and Juragua, Cuba, may be cited as an example of complex history. Magnetite and some

[15] Grout, F. F., and Broderick, T. M., "The Magnetite of the Eastern Mesabi Range, Minnesota," Bull. Minn. Geol. and Nat. Hist. Survey, in press.

hematite were deposited almost contemporaneously by hypogene solutions. Some of the specular hematite was altered to magnetite, perhaps by the dikes found in the ore-bodies. At about the same time some of the magnetite was replaced by hematite, yielding intergrowths of the same type as the hypogene replacements of magnetite seen in the Isle of Elba hematite crystals, but which, in the Cuban ores apparently may be formed by surface waters. In addition to these ores are the softer oxides which are not readily studied in polished section.

This study was taken up at the suggestion of Professor Lindgren, whose interest and suggestions are especially appreciated. The writer is also indebted to Professor Warren for criticism and to Professors Palache of Harvard University and Grout of Minnesota for the loan of certain specimens.

THE BASAL PHASES OF THE DULUTH GABBRO NEAR GABAMICHIGAMI LAKE, MINNESOTA, AND ITS CONTACT EFFECTS.[1]

M. L. NEBEL.

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PREFACE.

During the summer of 1916 the author with two companions spent about two months in the Vermilion region, mainly in the neighborhood of Gabamichigami lake (Fig. 26), studying the granites and associated dike rocks and the mutual effects of the granites and the gabbro upon one another. In the course of the work Dr. Nebel became interested in the peripheral phases of the gabbro and its metamorphic effects upon the rocks with which

[1] This paper is an abstract of portions of a dissertation that had been presented to the faculty of the University of Illinois in partial fulfillment of the requirements for the Ph.D. degree.

it is in contact. He believed he had evidence that the gabbro had contributed material to the metamorphosed rocks and that among the contributions were the components of sulphides like those occurring at Sudbury, Ont. The evidence is partly direct and partly indirect. The latter is largely petrographic. But, since it has a bearing upon the origin of the sulphides, it was

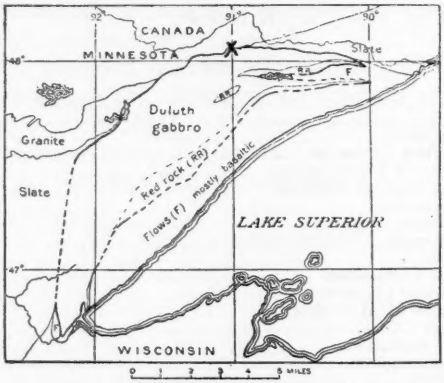


FIG. 26. Sketch map of the Duluth gabbro area. × indicates approximate location of Gabamichigami Lake.

discussed at some length in the original article of which this is an excerpt.

Unfortunately Dr. Nebel died before he was able to prepare his material for publication. The abstract presented herewith was made from his manuscript thesis. The content and conclusions are the author's. Necessarily there has been some editing, but this has been confined to a few verbal changes and the omission of parts of the original that are not essential to the understanding of the author's views.—W. S. Bayley.

INTRODUCTION.

Gabamichigami Lake is in northeastern Minnesota, near the east end of the Vermilion iron-bearing district, about eight miles

south of the International boundary line. It lies along the contact of the Keweenawan "Duluth gabbro" with the older rocks of the Algonkian and Archean systems which underlie it in position.

The succession in the neighborhood of the lake is:

Algonkian.

Keweenawan—Duluth gabbro.

Upper Huronian—Gunflint (iron-bearing) formation.

—Pokegama quartzite(?)

Lower-Middle Huronian—Knife lake slate.

—Ogishke conglomerate.

Archean.

Keewatin series—Ely greenstone.

Since the reasons for recognizing these divisions[2] have already been given and the rocks of the several formations have already been sufficiently described[3] it is unnecessary to discuss them further in this place. In this article attention is devoted exclusively to the Duluth gabbro and its metamorphic effects.

THE DULUTH GABBRO.

The Duluth gabbro is generally believed to be a laccolith[4] of enormous size. Its dip is about 10° S. Its base is said to follow the contact between the Animikie and the base of the Keweenawan, in general, but in the Vermilion district it departs from that plane, and cuts across the Lower Huronian and even the Archean greenstones. It follows close to the base of the Ani-

[2] Van Hise, C. R., and Leith, C. K., "Geology of the Lake Superior Region," U. S. Geol. Survey, Mon. 52, p. 118, 1911.

[3] Clements, J. M., "The Vermilion Iron-bearing District, Minnesota," U. S. Geol. Survey, Mon. 45, 1903.

[4] Since this mass is believed to rest upon a sunken floor, and not upon a comparatively level floor as in the case of typical laccolites, Grout (Grout, F. F., "The Lopolith; An Igneous Form Exemplified by the Duluth Gabbro," *Amer. Jour. Sci.*, Vol. XLVI., pp. 516–522, 1918) suggests that it be called a "lopolith." Lopolites are defined as large, comparatively thin, centrally sunken intrusions, which differ from laccolites not only in these points of size and form, but probably also in the mechanics of their intrusion. The maximum thickness of the Duluth gabbro is estimated at about 50,000 feet, its area at 15,000 square miles and its volume at 50,000 cubic miles.—W. S. B.

mikie from near Gunflint Lake west almost to Gabimichigami Lake, and there it is supposed to cut across the Lower Huronian and the Archean.

It has been shown above, however, that much of the metamorphosed material on the east side of Gabimichigami Lake which has been assigned to the Lower Huronian is probably of Upper Huronian age and belongs at the base of the Animikie. This rock rests directly on the Archean greenstones and is between them and the gabbro, so that it seems probable that at least as far west as the west end of Gabimichigami Lake the gabbro is still following close to the base of the Animikie, and not cutting across the Lower Huronian and Archean. It is the old erosion surface at the base of the Animikie which cuts across these older rocks and the gabbro merely follows that surface. The fact that Animikie rocks (Gunflint formation) have been found along the north border of the gabbro several miles farther west, on Disappointment Lake, suggests that perhaps even that far west the gabbro is still following the base of the Animikie. This affords better proof than ever of the laccolithic nature of the gabbro.

PETROGRAPHIC CHARACTER.

The main mass of the gabbro in the vicinity of Gabimichigami Lake is a basic, coarsely granular dark brown or black olivine gabbro. It, however, varies locally from fine-grained granulitic phases with grains a millimeter or less in length to very coarse-grained, almost pegmatitic phases in which plagioclase and augite crystals are sometimes 10 to 15 cm. in length.

Gray plagioclase is usually the most abundant constituent, and with it in various proportions occur augite, hypersthene, olivine, magnetite, biotite, chalcopyrite and pyrrhotite.

The plagioclase is a twinned labradorite, varying from about $Ab_{50}An_{50}$ to $Ab_{35}An_{65}$. It is frequently crowded with what are apparently hematite inclusions consisting principally of tiny black or dark brown needles and plates which are arranged in lines parallel to different crystallographic planes. Such inclusions have

been studied in detail by Anderson,[5] and he concludes that they are hematite lamellæ, which have been formed by unmixing of an originally homogeneous solid solution of the feldspar and hematite (or a ferric compound) in such a manner that thin hematite lamellæ have separated along structural planes (translation planes) of the feldspar."

The augite is a pink titaniferous, slightly pleochroic augite, containing rows of platy inclusions as described and figured by Bayley,[6] who suggested that they are due to the decomposition of the pyroxene along solution planes. As an alternative possibility, it might be suggested that they have an origin similar to that of the hematite inclusions in feldspar; that is, they may have been formed by an unmixing of an orginally homogeneous solid solution of augite and ilmenite (or rutile) in such a manner that the ilmenite separated out along structural planes of the augite. The augite sometimes contains inclusions in the form of opaque needles (probably ilmenite), which are often arranged in rows parallel to crystallographic planes.

Olivine is practically always present. It is usually quite fresh, though sometimes it has been slightly serpentinized or shows spongy magnetite in tiny clumps and dendritic masses along its cracks.

Hypersthene, magnetite and brown biotite are always present in small amounts, and apatite prisms are not uncommon accessories.

Small amounts of pyrrhotite and chalcopyrite were observed in it at four different localities:

Specimens of the sulphide-bearing gabbro from Gabimichigami Lake when polished and studied under the microscope, showed pentlandite frequently present, in addition to the other two sulphides.

Order of Crystallization.—The order of crystallization in the gabbro, as recorded by the minerals now present, was as follows:

[5] Anderson, Olaf, "On Adventurine Feldspars," *American Journal of Science*, ser. 4, Vol. 40, pp. 351–399, 1915.

[6] Bayley, W. S., "Basic Massive Rocks of the Lake Superior Region," *Jour. of Geol.*, Vol. 1, p. 703, 1893.

(1) Apatite; (2) magnetite, olivine, and augite in very minor amounts; (3) labradorite; (4) most of the olivine; (5) most of the augite (and hypersthene); (6) most of the magnetite; (7) biotite; (8) pyrrhotite; (9) chalcopyrite and pentlandite; (10) serpentine.

Contrary to the usual course of crystallization, the magnetite, olivine and augite crystallized only in very small amount prior to the separation of the plagioclase and by far the greater portion of these minerals crystallized later than the plagioclase. All three occur for the most part in irregular, often angular or wedge-shaped masses between idiomorphic plagioclase crystals and moulded around them. The augite was at least in part later than the olivine, since it very frequently occurs in the form of rims around the latter, either entirely or partially surrounding it, as described by Bayley.[7]

However, the periods of crystallization were not always sharp; there was more or less overlapping of 3 and 4, 3 and 5, and 5 and 6, above. Occasionally the augite and feldspar crystallized simultaneously, resulting in an intergrowth of the two in which tongues of augite extend into the adjacent plagioclase. Such an intergrowth was figured by Bayley,[8] and a similar one is shown in Pl. XIII., *a*.

Rarely olivine shows a similar intergrowth, but only one instance was seen in the sections examined (Pl. XIII., *b*).

Magnetite and augite sometimes show similar structures which may be due to primary intergrowth. This is a very abnormal feature, however, and is rarely seen (Pl. XIII., *d*).

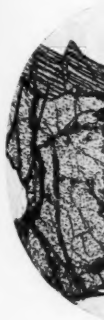
Magnetite is often later than augite and olivine, as well as plagioclase, as it is found surrounding and penetrating them in such a manner as to suggest corrosion of the older mineral and partial replacement by the magnetite (Pl. XIII., *c*).

Biotite occurs very largely as rims around magnetite, or as plates with a core of magnetite, and is particularly common where magnetite and feldspar are in contact (Pl. XIV., *a*). It

[7] Bayley, W. S., "Basic Massive Rocks of the Lake Superior Region," *Journal of Geol.*, Vol. 1, p. 706, 1893.

[8] *Op. cit.*, p. 709, Fig. 5.

PLATE XIII.



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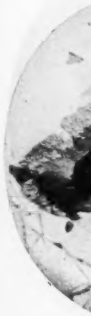

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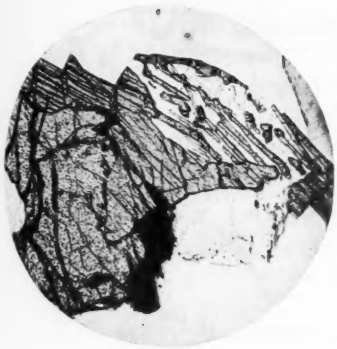

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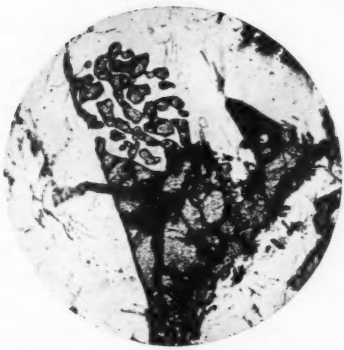
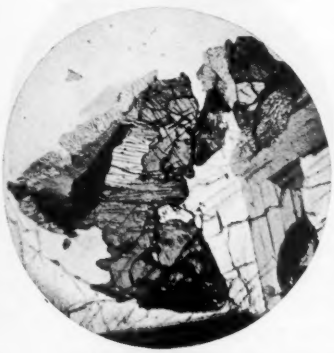


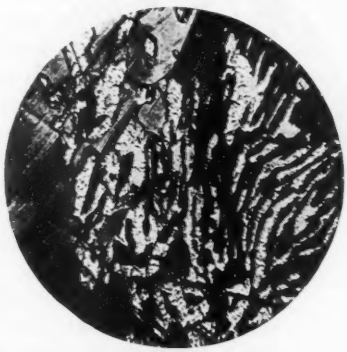
b.

FIG. *a*. Primary intergrowth of augite (gray mineral showing cleavage), and plagioclase (white) The gray mineral on the right is olivine. Parallel nicols, × 38.

FIG. *b*. Intergrowth of olivine and plagioclase in gabbro. Olivine (gray) is partially altered to serpentine (black). The small grains of olivine are in optical continuity with the large grain. Parallel nicols, × 43.



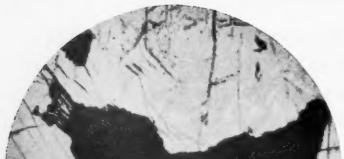
c.



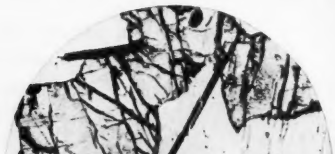
d.

FIG. *c*. Gabbro showing corona-like intergrowth surrounding biotite, which partially surrounds magnetite. The magnetite seems to be later than the augite (dark gray, and full of cracks). Nicols crossed, × 16.

FIG. *d*. Gabbro showing vermicular intergrowth of magnetite (black) and augite (gray) with rough surface. Parallel nicols, × 164.



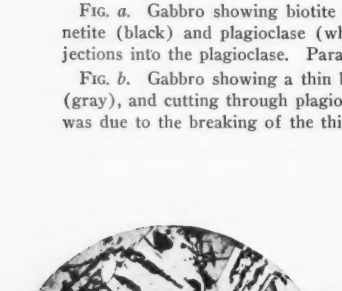
a.



b.

FIG. *a*. Gabbro showing biotite (dark gray) on the contact between magnetite (black) and plagioclase (white), and sending slender, finger-like projections into the plagioclase. Parallel nicols, × 34.

FIG. *b*. Gabbro showing a thin blade of biotite (black) penetrating olivine (gray), and cutting through plagioclase (white). The fracture in the biotite was due to the breaking of the thin section. Parallel nicols, × 37.



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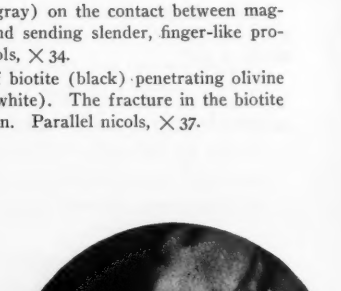


d.

FIG. *c*. Gabbro showing grains of chalcopyrite and pyrrhotite (black) replacing plagioclase (white) parallel to the cleavage, and penetrating biotite (dark gray) along cleavage planes. The gray mineral at the bottom is olivine. Parallel nicols, × 16.

FIG. *d*. Polished sulphides in gabbro. Veinlets of chalcopyrite (dark gray) cutting through pyrrhotite (light gray). The black spots are pits in the surface of the specimen. Reflected light, × 530.

seems to be what Sederholm[9] calls a "synantectic mineral." It occurs also on the contact of augite and plagioclase, and olivine and plagioclase. It is probably post-magmatic or late magmatic in origin, due perhaps in some cases to reaction between magnetite or a ferro-magnesian silicate with the plagioclase in contact with it, and in others to the pneumatolytic action of magmatic gases. When thin plates or blades of biotite are found cutting across plagioclase crystals and penetrating olivine, or cutting the contact of plagioclase and olivine or augite at a sharp angle they cannot well be explained by any other hypothesis than that of pneumatolysis (Pl. XIV., *b*).

Occurrence of Sulphides.—The sulphides occur in small grains with irregular, rounded or angular outlines cutting or embaying any of the silicates and magnetite. They are most abundant in labradorite, and long, slender grains or rows of angular grains penetrate it along cleavage planes (Pl. XIV., *c*). Frequently individual grains are connected by narrow stringers of the sulphides. These grains consist of a single sulphide, or of an intergrowth of pyrrhotite and chalcopyrite, or of these two and pentlandite. The chalcopyrite is always definitely younger than the pyrrhotite, and cuts it in narrow veinlets (Pl. XIV., *d*). The pentlandite is always intimately associated with the chalcopyrite, and the two form parallel intergrowths of narrow bands or narrow wedge-shaped masses. Sometimes chalcopyrite appears to be cutting or penetrating the pentlandite grains, and vice versa. They are probably of about the same period of formation.

These sulphides are believed by the writer to be of magmatic origin, and to belong to a late stage in the solidification of the gabbro itself. They were deposited before the formation of serpentine, since serpentine-filled cracks traverse chalcopyrite grains. Serpentinization probably accompanied dynamic metamorphism of the gabbro, since cracks filled with serpentine cut through strained labradorite grains, whose twinning lamellæ are offset on opposite sides of the crack.

Intergrowths.—Many sections of the gabbro contain fine inter-

[9] Sederholm, J. J., "On Synantectic Minerals," Com. Geol. Finland, No. 48, 1916.

growths of two minerals which form narrow rims around olivine and resemble the coronas, or reaction rims which in many rocks surround that mineral where it is in contact with plagioclase. The intergrowth consists of slender, vermicular rods of a colorless, highly refracting mineral lying in a matrix of plagioclase. The highly refracting mineral has an index of refraction which is about the same as that of the augite in the gabbro, and although the rods are not large enough for accurate determination it is probably augite. Bayley, who studied this feature of the gabbro in 1892,[10] considered it augite, principally because "the augite of the rock frequently sends out prolongations of its own substance into the surrounding plagioclase, and the ends of these prolongations have characteristics that are identical with those of the more highly refractive component of the intergrowths." The plagioclase of the intergrowth has a higher index of refraction than the labradorite of the gabbro, and is probably a more basic plagioclase, perhaps about $Ab_{35}An_{65}$. In a few instances the writer found in it albite twinning lamellæ the extinction of which was that of a basic labradorite. Its composition probably varies a little, however, as a single grain of plagioclase sometimes shows wavy extinction. The plagioclase of the intergrowth is never optically continuous with the adjacent more acid labradorite, and it is usually made up of several grains with different optical orientation, rather than of a single grain.

The intergrowth is most abundant at the contact of olivine and plagioclase, but it also occurs between biotite and plagioclase (Pl. XV., *a*), and rarely between augite and plagioclase. It may form a rim around the olivine, or occur in small clumps at points along the contact of the olivine and plagioclase. In such clumps, and frequently in the large rims, the rods of augite have a divergent arrangement, and always diverge toward the plagioclase. The intergrowth has a rounded or wave-like front which is convex toward the plagioclase, never toward the olivine, and which is always invasive in the plagioclase (Fig. 27). The

[10] Bayley, W. S., "A Fibrous Intergrowth of Augite and Plagioclase, Resembling a Reaction Rim, in a Minnesota Gabbro," *Amer. Jour. Sci.*, 3d series, Vol. 43, pp. 505–520, 1892.

olivine in this rock was formed for the most part later than the feldspar, and surrounds and encloses idiomorphic crystals of labradorite. Where the intergrowth lies on the contact of olivine with such crystals of labradorite, there can be no doubt that it has actually replaced the feldspar. Sometimes only the centers of such crystals remain unreplaced, and have curved,

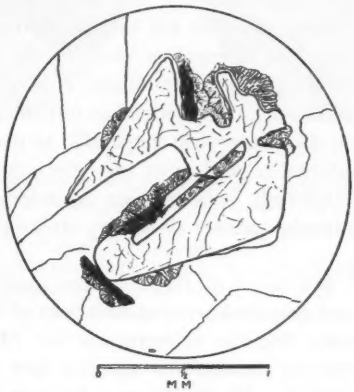


FIG. 27. Corona-like intergrowths of plagioclase and augite around olivine enclosing laths of plagioclase.

corroded outlines, while the fibrous intergrowth fills out the shape of the original crystal (Pl. XV., *b*, and Fig. 27). In such cases the inclusions in the original labradorite crystals frequently extend unchanged in abundance or in direction into the intergrowth (Pl. XV., *c*). All gradations may be traced in a single section from fresh prisms of labradorite enclosed by olivine to others which consist entirely of the intergrowth, but which still have the outlines of idiomorphic labradorite crystals. There is never the slightest suggestion of any invasion or replacement of olivine by the intergrowth.

Bayley, who studied this intergrowth in 1892,[11] interprets it as a granophyric intergrowth of plagioclase and pyroxene.

[11] Bayley, W. S., *op. cit.*, p. 520.

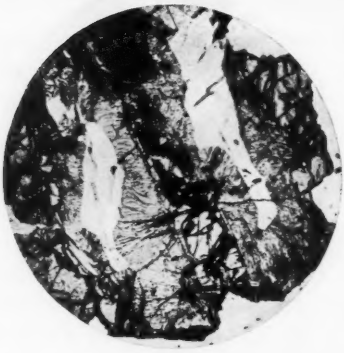
Such a mode of origin does not agree with all of the features of the intergrowth, however. It is true that the augite in the gabbro sometimes forms intergrowths with the labradorite, and in such cases the intergrowth is obviously primary, the augite tongues are connected and optically continuous with a large grain of augite, and the feldspar of the intergrowth is a labradorite optically continuous with a large labradorite grain nearby. Such primary intergrowths do not have an intrusive relation to the labradorite. The corona-like intergrowth, on the other hand, replaces feldspar which crystallized in idiomorphic prisms before the crystallization of the augite or olivine. The fact that the inclusions in the intergrowth lie parallel to those of the surrounding labradorite, regardless of the orientation of the feldspar of the intergrowth, indicates that the intergrowth has replaced the labradorite without disturbing its original inclusions (Pl. XV., *c*).

Sederholm[12] has reviewed the literature dealing with such intergrowths, and described some observations of his own. He favors the theory that the intergrowths are of a secondary nature and formed by metamorphic agencies later than the solidification of the rock. He emphasizes the fact that they are entirely absent from gabbros and diabases which have undergone no later metamorphism, while they are common in old basic rocks which have been metamorphosed. As to the process by which they were formed, he stated, "The process by which the coronites have originated has not consisted exclusively in a reaction between the adjacent minerals. These minerals have supplied only a part of the constituents of the coronas, while another part has been transported in solution from more distant places of the same rock masses."

In the writer's belief the evidence is conclusive that the corona-like intergrowths in the Duluth gabbro are replacements of plagioclase, and that the replacement took place after the main period of solidification of the rock. The evidence is not con-

[12] Sederholm, J. J., "On Synantectic Minerals," *Bull. Comm. Geol. de Finlande*, Bull. 48, pp. 9–47, 1916.

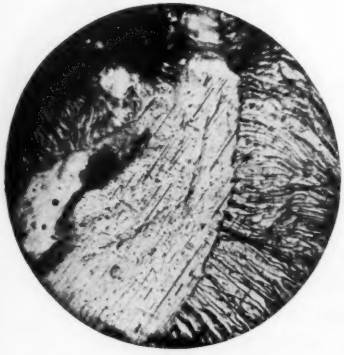
a.



b.

FIG. *a*. Corona-like intergrowth of plagioclase and pyroxene surrounding slender blade of biotite nearly vertical in photograph. At top and bottom is plagioclase (light gray), and to left and right are grains of olivine (gray, with rough surface). Parallel nicols, × 100.

FIG. *b*. Plagioclase laths (white) enclosed by olivine (dark gray and full of cracks). The plagioclase has been almost completely replaced by the fibrous intergrowth of plagioclase and pyroxene, so that mere cores are left. Parallel nicols, × 16.

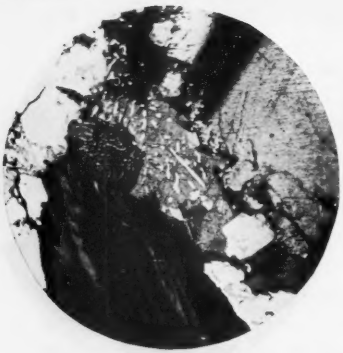


c.

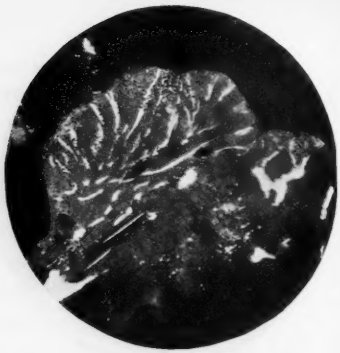
d.

FIG. *c*. Gabbro showing inclusions (black) in plagioclase (white) and extending into the intergrowth which has replaced the plagioclase. Parallel nicols, × 118.

FIG. *d*. Granulitic gabbro. Plagioclase is white, augite and hypersthene are light gray without much relief, olivine is darker gray, and stands in relief, magnetite is black. Parallel nicols.



a.



b.

FIG. *a.* Contact between granite dike (on the left) and its wall rock of gabbro (on the right), showing myrmekite grains (in center). The myrmekite lies on the contact between labradorite grains (light gray, on the right) and orthoclase (black, on the left). In the center, above the myrmekite, are a few quartz grains. Nicols crossed, × 44.

FIG. *b.* Enlarged view of one of the myrmekite grains in *a*. The myrmekite is convex towards the orthoclase. The slender, vermicular white areas are quartz, lying in a matrix (dark gray) of albite, or oligoclase. Nicols crossed, × 170.

c.

d.

FIG. *c.* Polished sulphides from contact-metamorphosed quartzite near gabbro, showing replacement of pyrrhotite (large white, pitted areas) by unknown grayish-white sulphide. Replacement starts from opposite sides of cracks, and proceeds until the pyrrhotite disappears entirely, or only a small core remains. Reflected light, × 30.

FIG. *d.* Another portion of the same polished specimen, showing chalmersite (?) (faint white) replaced by pyrrhotite (gray) along cracks. A small tongue of chalcopyrite has penetrated along a crack from the lower right-hand side of the photograph (*cp*). Reflected light, × 526.

clusive, however, as to whether the process was a phase of the last stages of crystallization of the magma, or whether it was a metamorphic process which took place after the rock was completely solidified. The fact that the gabbro shows many metamorphic features indicates that a metamorphic origin for the intergrowth is possible.

LOCAL PHASES OF THE GABBRO.

There are local variations in the texture of the gabbro, and in the relative abundance of the different constituents. The following phases were recognized in the immediate vicinity of Gabimichigami Lake: (*a*) Normal coarse-grained olivine gabbro, (*b*) hyperite, (*c*) norite, (*d*) coarse-grained ophitic gabbro (gabbro pegmatite), (*e*) fine-grained granulitic gabbro, (*f*) fine-grained ophitic gabbro.

The gabbro, hyperite and norite are composed of the same essential minerals, but in widely differing amounts as follows:

	Gabbro.	Hyperite.	Norite.
Labradorite	69.9	49.6	40–50
Augite	11.8	12.2	2–3
Olivine	11.0	24.8	
Biotite	4.2	.4	3–4
Hypersthene	2.2	9.8	50–40
Magnetite	.9	3.2	5–4

The norite was observed as a border phase of the main mass of the gabbro where it approaches an area of Ely greenstone at the southwest corner of the lake. It becomes finer-grained toward the border of the mass, with plagioclase grains a millimeter or less in diameter, but does not show the granulitic texture exhibited by some of the other fine-grained border phases. The texture is usually distinctly ophitic.

The plagioclase averages about labradorite ($Ab_{40}An_{60}$), but it is often zoned with about $Ab_{25}An_{75}$ in the center and about $Ab_{45}An_{55}$ on the border of the crystals. The tiny inclusions so common to the plagioclase of most of the gabbro become less abundant as the rock becomes finer-grained. The plagioclase

grains are often fractured and show strain shadows, which are probably the result of movements in the mass before complete solidification and during the final cooling.

The hypersthene is deeper in color and more strongly pleochroic than most of the hypersthene which occurs in small amount in the coarse gabbro, and is frequently altered more or less completely to a grayish-green, fibrous serpentine (bastite).

The augite is a very minor constituent. When present it is usually much altered to a fibrous, pale green hornblende.

The biotite frequently occurs as large poikilitic plates enclosing indiscriminately grains of all of the other constituents. These plates have probably developed subsequent to, or as the result of, the metamorphism which produced the strained feldspars and the altered hypersthene, since fresh biotite showing no signs of bent or twisted lamellæ encloses grains of greatly altered hypersthene and of fractured and strained plagioclase. Small flakes of biotite are also frequently intergrown with the hornblende and serpentine resulting from the alteration of the hypersthene.

Away from the border the norite becomes coarser grained, and locally becomes much richer in plagioclase.

At two localities along the shores of Gabimichigami Lake an extremely coarse-grained phase of the gabbro was observed, which might almost be called a gabbro-pegmatite. The pegmatite occurs in very irregular stringers and lenslike masses which grade into normal gabbro on either side. Its exposed surface is covered with a coating of green chrysocolla due to the weathering of chalcopyrite, which is disseminated through it in small grains.

The pegmatite consists of the same minerals usually occurring in the gabbro, with the addition of chalcopyrite and pyrrhotite and a little pentlandite. Magnetite occurs later than the plagioclase, augite or olivine, in wedge-shaped masses between these minerals, and again it occurs in intimate intergrowth with augite as if it crystallized simultaneously with it.

A peculiar feature of the rock is the frequent development in

it of the corona-like intergrowth of plagioclase and pyroxene around olivine grains where they come in contact with plagioclase.

Fine-grained Granulitic Gabbro.—At one locality on Gabimichigami Lake there is a massive, fine-grained, dark gray rock which is intruded by the normal, coarse-grained gabbro in a very irregular manner (Fig. 28). This fine-grained rock at first

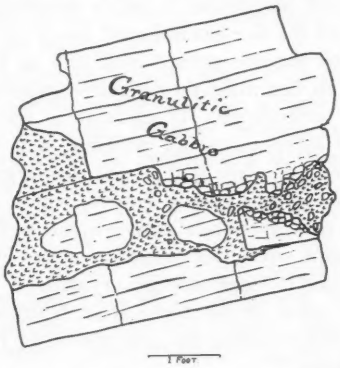


FIG. 28. Tongue of coarse gabbro cutting granulitic gabbro and enclosing fragments of latter.

glance looks very much like some of the metamorphosed quartzites, and was so interpreted by early observers.[13] It is crossed by joint planes very nearly horizontal and vertical, producing on weathered surfaces an appearance very much like that of bedding, which accentuates the resemblance to the metamorphosed quartzites or graywackes. This jointing was, however, produced after the intrusion of the gabbro, for the joint planes extend across the contact of the two rocks.

The tongues of the coarse gabbro that penetrate the fine-grained rock are crowded with fragments of the latter, and inclusions are abundant in the coarser gabbro for a distance of 40 or 50 feet from the contact. They range from small pieces to

[13] Winchell, Alexander, Minnesota Geol. & Nat. Hist. Survey, 15th Ann. Rept., p. 171, 1887.

large boulders a meter or more across. Most of the inclusions are well rounded, and must have been friable at the time they were picked up by the gabbro. There is no sign of chilling of the gabbro along the contact or in the narrow apophyses which penetrate the intruded rock. It is quite as coarse-grained on the contact as in the interior of the gabbro mass. The contact is fairly sharp, and in a single thin section one may see portions of large grains of plagioclase or augite extending between the smaller grains of the fine-grained rock along an irregular line.

In thin section the fine-grained rock may be seen to contain the same minerals that make up the coarse gabbro, but in somewhat different proportions. It contains a relatively greater amount of the ferro-magnesian minerals, and has a specific gravity of 3.00–3.10, while that of the coarse gabbro is 2.76–2.94. The rock is a fine-grained gabbro, with a granulitic texture. All its constituents are allotriomorphic, well rounded, and of about the same size. Occasionally, augite, hypersthene, or olivine is developed in large poikilitic crystals.

Bayley[14] has called similar rocks from Northeastern Minnesota granulitic gabbros, using the term applied by Judd to similar rock from Scotland.[15]

The fine-grained gabbro on Gabimichigami Lake is a granulitic gabbro (Pl. XV., *d*) showing mineralogical variations similar to those described by Bayley. Of eleven sections cut from different portions of the massive rock and the inclusions in the coarse gabbro, no two are exactly alike, and a great variation in mineral composition is shown.

The granulitic texture as first applied to this type of gabbro by Judd was explained as due to the crystallization of a moving magma in which the grains as they formed were rolled around and prevented from interlocking freely. The fine-grained granulitic border phase of the Duluth gabbro probably crystallized under some such conditions. The fact that there are definite

[14] Bayley, W. S., "Basic Massive Rocks of the Lake Superior Region," *Journal of Geology*, Vol. 3, pp. 1–20, 1895.

[15] Judd, J. W., "On the Gabbros, Dolerites and Basalts of Tertiary Age," *Quart. Jour. Geol. Soc.*, Vol. 42, p. 49, 1886.

intrusive relations between this phase and the normal coarse-grained gabbro shows that the intrusion of the gabbro magma was not a simple process, the result of a single impulse, but that it must have been the result of successive impulses. The first intrusion must have been small in amount since it cooled rapidly enough to produce a fine-grained rock. It was also of material higher in iron and magnesia than the great mass of material which was later intruded. This is indicated by the predominance of ferromagnesian minerals, and is substantiated by the few analyses which have been made.[16]

Where the granulitic gabbro was subject to movement during the period of crystallization, the granulitic texture resulted. In some portions of the mass, however, movements must have ceased while a portion of the magma was still liquid, and the remaining portion crystallized under static conditions to form the large poikilitic pyroxene, olivine and feldspar grains. While the granulitic gabbro was still hot, large amounts of the still liquid magma forced its way into the portion already solidified, entering fractures and breaking off fragments which became engulfed in the intrusive. The new material was in sufficient quantity and at such a temperature that it was permitted to crystallize slowly and develop a coarse-grained rock.

Outliers.—In spite of its enormous extent, the Duluth gabbro contains few apophyses extending out into the surrounding rocks. Clements[17] refers to two outliers of gabbro which are believed to be offshoots of the main mass, although no connection between them can be traced.

One of these is a sill on the little point of land forming the east side of "The Narrows," as Winchell called it, through which one enters the south bay of the lake. The lower part of the sill consists of a medium-grained gabbro with a texture which might be said to be intermediate between the ophitic and granulitic. The minerals are the same as in the normal gabbro,

[16] See Bayley, W. S., "Basic Massive Rocks of the Lake Superior Region," *Journal of Geology*, Vol. 3, p. 10, 1895.

[17] Clements, J. Morgan, "The Vermilion Iron-bearing District, Minnesota," Mono. 45, U. S. G. S., p. 398, 1903.

with the addition of brown hornblende, which occurs as hypidiomorphic grains scattered through the rock. They are probably primary and not derived from the alteration of augite.

The crystallization of the rock, as it is recorded by the minerals now present, seems to have begun with the separation of magnetite and perhaps small hornblende crystals, followed by the crystallization of the plagioclase, together with the minerals which now form the inclusions in it. Augite and olivine crystallized during the same period and for the most part later than the feldspar. Hornblende shows no definite age relation to the other minerals, and seems to have crystallized at any period, whenever conditions were favorable for its production. It sometimes forms idiomorphic crystals enclosed by feldspar, and again is intergrown with augite which is definitely younger than feldspar. At a late period in the final stages of crystallization biotite was formed, probably by what Sederholm[18] calls "Autometamorphic" processes.

This medium-grained rock grades downward into a fine-grained ophitic gabbro which contains the same minerals, but in slightly different proportions. Their rounded outlines suggest that, like the granulitic gabbro, this rock had only partially crystallized when further movement of the magma took place, preventing the close interlocking of the minerals and the formation of sharp angles, and resulting in somewhat rounded forms. It grades upward through intermediate rocks to a black hornblende rock.

All of these rocks are very dark and contain variable amounts of hornblende. Values of 3.18–3.19 were obtained for the specific gravity of the gabbro, 3.23, 3.25, and 3.26 for that of the intermediate rocks, and 3.31–3.32 for that of the black hornblende rock.

In thin section the intermediate rocks have many characters in common with the gabbro into which they grade.

The black hornblende rock, into which the intermediate phases grade, is a heavy, jet-black, granular rock with a glistening appearance due to the reflection of light from the cleavage plates

[18] Sederholm, J. J., "On Synantectic Minerals," *Bull. Comm. Geol. de Finlande*, No. 48, p. 4, 1916.

of hornblende. A few areas of light-colored minerals sometimes gives it a mottled appearance. In thin section it is like the intermediate rocks described above, except that it has a much greater abundance of dark brown hornblende. The relative proportions of augite and olivine present vary widely. In one section augite was practically absent, while olivine made up about 15 per cent. of the section.

This rock is a very hornblendic gabbro. The great preponderance of hornblende would almost place it with the hornblendites, but it seems to be more closely related to Rosenbusch's[19] hornblende peridotites. Its close relation to the gabbro, and its evident derivation from a gabbro magma also make it more like the hornblende peridotites.

This hornblende peridotite is apparently a differentiate of the gabbro of the sill, but the field data are insufficient to permit a satisfactory determination of the mode of differentiation.

GRANITE DIKES.

In the early reports of the Minnesota Geological and Natural History Survey, in the final report,[20] and in Clements's monograph[21] there are mentioned a number of dikes of red granite which cut the gabbro at several localities. Grant[22] reports one locality at which the granite occurs in large masses which send offshoots into the surrounding gabbro. The dikes are said to vary in width from half an inch to ten feet and to consist of quartz, orthoclase, acid plagioclase and biotite.

This red granite bears a superficial resemblance to the much older Archean and Algonkian granites (Giant's Range granite, Snowbank Lake granite, etc.), but it is intrusive in the Duluth gabbro, is of Keweenawan or post-Keweenawan age, and has seldom been found in large masses. It is here regarded as a hypabyssal phase of the red rock which is so abundant in the

[19] Rosenbusch, "Micr. Phys. der Min. u. Gesteine," Bd. II., pp. 457–463, 1907.

[20] Winchell, N. H., and others, "The Geology of Minnesota," Minnesota Geol. and Nat. Hist. Survey, Final Report, Vol. 4, pp. 458 and 479, 1899.

[21] Clements, J. M., "The Vermilion Iron-bearing District, Minnesota," Mono. 45, U. S. Geol. Survey, p. 422, 1903.

[22] Grant, U. S., "The Geology of Minnesota," Minnesota Geol. and Nat. Hist. Survey, Vol. 4, p. 458, 1899.

upper portion of the Duluth laccolith and which is frequently intrusive in it. It is more like Irving's "Augite syenites"[23] and Bayley's "granular red rock,"[24] than any other of the red rocks which have been described.

On Gabimichigami Lake one of these dikes, 11–12 inches wide, is found cutting both the gabbro and its fine-grained granulitic border phase. It apparently occupies a fault fracture, although there was no way to measure the displacement, which may have been slight. This possibility is of some interest in connection with certain metamorphic features shown by the gabbro.

Masses of the granite are often seen "frozen" to the wall, and narrow stringers of the granite from a fraction of a millimeter to 2 inches wide, and ½ to 2 or 3 inches apart occupy sheeting planes in the gabbro which is often noticeably sheared on each side of the dike for several inches. Occasionally platy fragments of the gabbro are included in the granite.

Although the dike is very narrow, there is no sign of chilling along the contact. The rock is quite uniform in grain, the feldspar grains being about 0.2 to 0.5 cm. in diameter, and the quartz grains a little smaller. In addition to quartz, both pink and gray feldspar can be distinguished microscopically, the latter sometimes showing twinning striations. A dull black mineral is present in small amount, and sometimes gives a gray tinge to the rock.

Chemical Composition.—The granite is closely related chemically to the Keweenawan "red rocks." A partial analysis was made for the writer by J. M. Lindgren of the University of Illinois, and the results are indicated in line I. below. It is most like the red rock, the composition[25] of which is given in line II. A noticeable feature is its relatively high soda content.

[23] Irving, R. D., "The Copper-bearing Rocks of Lake Superior," Mono. 5, U. S. Geol. Survey, p. 112, 1883.

[24] Bayley, W. S., "The Eruptive and Sedimentary Rocks on Pigeon Point, Minnesota, and their Contact Phenomena," Bull. 109, U. S. Geol. Survey, pp. 50–53, 1893.

[25] Quoted by Winchell, N. H., "The Geology of Minnesota," Minnesota Geol. and Nat. Hist. Survey, Final Report, Vol. 5, p. 303.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	MgO	K_2O	Na_2O	H_2O	
I.	61.89						3.31	4.12		
II.	61.09	15.34	5.74	3.69	3.10	1.33	3.41	3.65	1.80	99.15

Petrographic Characters.—In thin section the following minerals were recognized, and a careful measurement gave the proportions by volume indicated:

Quartz	29.7	Biotite	2.2	
Orthoclase	36.3	Zircon	0.2	
Albite	22.0	Kaolin and muscovite	2.0	Secondary.
Microline	3.8	Chlorite and calcite	0.5	Secondary.
Magnetite	3.3		100.0	

Although the section measured was cut from a chip selected at random from the main portion of the dike, inspection of hand specimens shows that it probably contains less than the average amount of biotite, since that mineral and magnetite are frequently present in sufficient amount to give a decided gray tinge to the rock.

In addition to the above minerals apatite is present in tiny prisms, but in such small amount that it does not appear in the geometric analysis. In one or two sections a few small grains of pale green diopside were seen.

Most of the quartz grains are hypidiomorphic, with imperfect crystal faces, and rounded contours which suggest partial resorption by the magma. The curved outlines and irregular shapes of many of the grains suggest corrosion. They are frequently enclosed by feldspar, and then show well-developed prismatic and pyramidal faces. Holmquist[26] called this the "margination structure," and states "Alle diese Strukturzüge (quartz de corrosion, quartz vermicule) sind dem Granit und Gneiss der metamorphischen Gebiete eigen, und sie kommen in ganz unmetamorphosierten Graniten nicht vor." Bäckström[27] interpreted similar phenomena in Swedish granite as follows: "The writer considers the differences from the hypidiomorphic struc-

[26] Holmquist, P. J., "Studien über die Granite von Schweden," *Bull. Geol. Inst. Univ. of Upsala*, Vol. 7, p. 116, 1906.

[27] Bäckström, H., "Vestanäfaltet," *K. Sv. Vet. Ak. Förh.*, Vol. 29, No. 4, pp. 9–13, and p. 116, 1897.

ture in these granites as owing to a sort of corrosion, but secondary not primary, due to the beginning of the crushing of the rock and probably also in some degree to the beginning of decomposition, and consequently not the result of circumstances accompanying the original crystallization of the granite magma." Eskola,[28] however, disagrees with most Fenno-Scandian geologists, who regard the corrosion as a secondary structure marking one of the most important differences between the Archean and post-Archean granites, and states: "In the opinion of the writer the simplest and most natural way to understand this structure is to regard it as a product of crystallization accompanied by magmatic corrosion. The physicochemical theories of the crystallization of solutions have shown that the phenomena of resorption may take place as a normal event in the regular course of crystallization, by reason of the progressive change of composition of the residual solution." The corrosion of the quartz in the granite of Gabimichigami Lake is best explained by magmatic corrosion, as postulated by Eskola. Some of the quartz, however, seems to have crystallized simultaneously with the feldspar, and the texture is granitic with quartz and feldspar grains mutually interfering and interlocking.

The orthoclase and albite crystallized simultaneously, and show mutually interfering and interlocking grains. The orthoclase is so turbid that its optical characters could not be accurately determined, but the high soda-content of the granite indicates that it is a sodic variety, perhaps anorthoclase. The albite is about $Ab_{90}An_{10}$. Both minerals are much altered and turbid with a fine dust of kaolin, and contain many minute flakes of colorless to pale green sericite. Sometimes the sericite is so abundant that it forms a felted mass of flakes all through the feldspar. Other secondary minerals are chlorite and calcite.

The orthoclase nearly always shows irregular sinuous or wavy patches which are clear and almost unaltered. Between crossed nicols these patches show polysynthetic twinning, and occasionally

[28] Eskola, Pentti, "On the Petrology of the Orijärvi Region in Southwestern Finland," *Bull. Comm. Geol. de Finlande*, No. 40, p. 23, 1914.

show an indistinct grating structure. Where only one set of twinning lamellæ are visible the symmetrical extinction is 18 degrees to 19 degrees, while that of the albite grains is only 13 degrees to 14 degrees. The material is, therefore, microcline. Its structure is probably a pressure phenomenon, produced by the same forces which caused the development of strain shadows and wavy extinction.

Occurrence of Myrmekite.—An interesting feature of this granite is the presence in it of the vermicular quartz-plagioclase intergrowth to which the name myrmekite was given by Sederholm.[29] This intergrowth consists of rods of vermicular quartz in plagioclase. Sometimes the plagioclase is striated and can be determined as an acid oligoclase. In other cases it is unstriated and can merely be determined as an acid plagioclase, since it has a higher index of refraction than adjacent orthoclase. The myrmekite frequently is present in the "wart-like" masses described by Sederholm, and these masses extend into orthoclase grains and present a convex surface toward them (Pl. XVI., *a*, *b*). Many of the myrmekite grains look strikingly like those figured by Sederholm in a recent paper reviewing the whole field of such phenomena.[30] (Compare Pl. XVI., *a*, of this paper with Figs. 20, 21 and 22, Plate IV., and Fig. 16, Plate III., and Fig. 37, Plate VII., of Sederholm's paper.)

After reviewing completely the literature of the subject and comparing the views of different authors, Sederholm discusses the different characteristics of myrmekite point by point, and concludes "that myrmekite cannot be regarded as primary in the strictest sense of the word, since it has crystallized within the borders of another mineral, replacing its substance. . . . A number of observations . . . seem to prove beyond doubt that the myrmekite of certain Rapakivi granites, and also of older pre-Cambrian rocks, has been formed before the final consolidation of all the mineral constituents of the magma in question. . . .

[29] Sederholm, J. J., *Bull. Comm. Geol. de Finlande*, No. 6, p. 108, 111–114, 1897.

[30] Sederholm, J. J., "On Syntantectic Minerals," *Bull. Comm. Geol. de Finlande*, No. 48, 1916.

The formation of the myrmekite may be either earlier, contemporaneous with, or later than the mechanical crushing of the rock, depending on the succession of the events at its metamorphism."

There seems to be a general agreement, according to Sederholm, that the process by which myrmekite is formed is a recrystallization of an isomorphous K—Na—Ca feldspar, or of orthoclase containing lime and soda in solid solution, by which plagioclase is formed. The potash is removed and the excess silica forms vermicular quartz rods in the plagioclase, the amount of quartz increasing as the plagioclase becomes more basic. Becke[31] and Luczizky[32] have measured many sections and shown that there is such a relation between the amount of quartz and the basicity of the plagioclase. Such a process of recrystallization best explains the phenomena noted in the Gabimichigami granite, especially since the orthoclase seems to be a sodic variety.

The myrmekite in the Gabimichigami granite agrees well with all of the features described by Sederholm. Some of the narrow stringers of granite consist almost entirely of quartz and myrmekite, and in such cases there is no reason to believe that Sederholm's suggestion is not the true one; that is, that the orthoclase has been completely replaced by myrmekite. In fact one can frequently find relicts of orthoclase which have not been completely replaced and can almost trace the gradation from grains of orthoclase which are just beginning to be replaced by a few grains of myrmekite, to those which have been completely replaced. A further significant feature is the presence of grains of quartz completely enclosed by myrmekite Orthoclase often contains such inclusions and quartz was evidently left undisturbed when the mineral recrystallized to form myrmekite.

Moreover, in the Gabimichigami granite there is practically always a core of plagioclase. Sometimes the plagioclase of the myrmekite is optically continuous with a larger crystal of albite;

[31] Becke, E., "Über Myrmekite," *Mitt. der Wiener mineralog. Gesellsch.*, Tschermak's "Min. u. Petr. Mitt., Vol. 27, pp. 381–390, 1908.

[32] Quoted by Sederholm, *loc. cit.*, p. 94.

more frequently the myrmekite lies between grains of plagioclase and orthoclase. In the small stringers of granite the myrmekite may have been derived from the calcic feldspar of the gabbro wall-rock and the orthoclase of the granite, invading the latter.

In these cases it seems likely that part of the lime and soda which replaced the potash of the orthoclase to form myrmekite may have been derived from the calcic feldspar of the gabbro forming the wall-rock of the dike (Pl. XVI., *a*). The distribution of the myrmekite indicates something of that sort. A bare half dozen or so grains of myrmekite were found in the sections of the main dike, and these were all either adjacent to the wall-rock or to fragments of it included in the dike. By far the greatest amount of myrmekite occurs in the small stringers of granite which run along sheeting planes parallel to the main dike, so that it is immediately adjacent to the feldspar of the gabbro, in which the requisite lime and soda are available. Sometimes parts of the stringers consists almost entirely of quartz and myrmekite. Other parts of the same stringer contain the usual orthoclase and albite in addition. Since these stringers are only a millimeter or a few millimeters in width, it would not require much transference of material in order to make the lime and soda available for the formation of myrmekite.

The labradorite of the wall rock is frequently turbid and altered to a mass of tiny colorless mica flakes. This alteration frequently takes place along cracks in the feldspar and extends inward on both sides of the cracks. This mode of alteration of the feldspar was found nowhere else in the gabbro except along the contact with the granite dike. Although no analysis is available and the mica flakes are too small for accurate determination, it is possible that the mica is a potash variety and that the potash set free when the orthoclase was replaced by myrmekite went into the mica of the altered labradorite. Thus we explain the derivation of the agents causing the change and the disposition of the products.

It remains to be determined whether this process resulting in the production of myrmekite belongs to the waning-period of

the plutonic activity, connected with the eruption of the rock, or to the beginning of a later period of metamorphism. In one of the sections studied, showing the contact of the dike and wall-rock, the minerals are fractured along a zone close to the contact, and slight displacement has taken place along the fractured zone. This fracturing is probably due to slight movements after the solidification of the granite. The significant feature in this respect is that myrmekite grains along the fractured zone are broken and the broken parts slightly displaced. This is regarded as good evidence that the myrmekite was formed prior to at least one period of metamorphism, and there is no evidence of more than one such period. With this in mind, it seems best to regard the myrmekitization in this case as a process connected with the last phases of the crystallization of the granite, rather than with a later metamorphism.

DIABASE DIKES.

Cutting the Duluth gabbro and all older formations in the Vermilion district are great numbers of basic dikes, which have been described by Minnesota geologists and those of the U. S. Geological Survey. These dikes are abundant in the vicinity of Gabimichigami Lake. They show no particular differences from those over the whole district. Clements's[33] description gives a good idea of their general character.

REGIONAL METAMORPHISM.

At a distance from the gabbro the Archean greenstones, which are believed to be old basic effusive rocks, and the Lower Huronian Ogishke conglomerates and the Knife Lake slates have suffered extensive metamorphism under mass static conditions. Their components have recrystallized without obliterating original structures, producing schists with features like those of rocks characterizing Grubenman's "meso-zone."

The Animikie quartzite and the Gunflint iron-bearing formation, both of the Upper Huronian series, were seen only in the

[33] Clements, J. M., "The Vermilion Iron-bearing District, Minnesota," Mono. 45, U. S. Geol. Survey, pp. 422–424, 1903.

immediate vicinty of the gabbro where they have been so thoroughly metamorphosed by the igneous rock that it is not possible to ascertain to what extent they have been subjected to regional metamorphism.

With reference to the iron formation, Grant[34] considered the original rock a glauconitic greensand with which there was more or less iron carbonate. This he believed was changed to quartz-magnetite-amphibole slates similar to the magnetite-actinolite slates or schists of other localities. These slates he believed were later metamorphosed by the gabbro to the rocks we now find.

Clements[35] seems to ascribe the metamorphism of the iron-foundation entirely to the action of the gabbro without any intermediate metamorphism of an anamorphic nature. He described ferruginous cherts, containing granules of limonite, which he believed were produced by the oxidation of ferrous silicate rocks. He found structures in the metamorphosed rocks which indicated to him that they were produced by recrystallization of the ferruginous cherts. This would, however, involve a previous oxidation of the iron (a katamorphic process) to form the limonite granules.

Zapffe[36] also believed that the metamorphosed iron-formation rocks were developed directly from ferruginous silicate and carbonate rocks by contact metamorphism, without intermediate metamorphism of any sort. He states that it is unlikely that the contact rocks were developed from ferruginous cherts, since such a change would involve a reduction of the iron, and this is an unusual change in the chemistry of the alterations of the Lake Superior iron-bearing formations.

Van Hise and Leith[37] came to a similar conclusion.

[34] Grant, U. S., "Contact Metamorphism of a Basic Igneous Rock, U. S.," *Bull. Geol. Soc. Amer.*, Vol. 11, p. 508, 1900.

[35] Clements, "The Vermilion Iron-bearing District, Minnesota," Mono. 45, U. S. Geol. Survey, pp. 384–387, 1903.

[36] Zapffe, Carl, "The Effects of a Basic Igneous Intrusion on a Lake Superior Iron-bearing Formation," ECON. GEOL., Vol. 7, p. 167, 1912.

[37] Van Hise, C. R., and Leith, C. H., "Geology of the Lake Superior Region," Mono. 52, U. S. Geol. Survey, pp. 549–550, 1911.

It seems probable to the writer that contact-metamorphism by the Duluth gabbro alone produced the present characters of the iron-formation and that they are not in the least due to regional metamorphism.

CONTACT METAMORPHISM.

Nearly all the rocks of the district as they approach the gabbro show the effects of its action upon them.

GREENSTONES.

The study of the contact metamorphism of the greenstones was complicated by the fact that metamorphosed Upper Huronian quartzite occurs overlying them at the point where these rocks approach most closely to the gabbro. This metamorphosed quartzite was considered a contact phase of the greenstones in the field, and it was only after microscopic study that its true character was recognized.

The greenstones were not found in direct contact with the gabbro, but where they outcrop a few hundred feet away they show features which are probably the result of contact metamorphism. They are black or dark gray instead of the usual green, and they have a granular appearance without the ophitic texture noticeable in the greenstones, a half mile or more from the contact.

In thin section the difference between the greenstones near the gabbro and those distant from it is still more evident. The metamorphosed rocks still consist principally of hornblende and plagioclase, with a little magnetite, but the hornblende is a dark brownish green or brown variety, instead of pale green as in the unmetamorphosed rocks, and magnetite is less abundant. Sometimes plagioclase laths remain and the ophitic texture is recognizable, but more frequently the feldspar has recrystallized to a mosaic of small polygonal grains and the texture is crystalloblastic. In some cases pale green diopside is present instead of the hornblende, or both may be present in the same section, either as small grains forming, with andesine, a granoblastic texture,

or in large poikiloblasts enclosing andesine grains. The diopside is regarded as having formed in place of the hornblende when the rock recrystallized. A small amount of pale blue tourmaline occurs in slender radiating crystals. It is quite similar in character to tourmaline found in most other rocks of the region where they have been metamorphosed by the gabbro, and is regarded as evidence that at least a small amount of gaseous material was contributed by the gabbro to the rocks which it intruded.

The features noted here agree for the most part with the metamorphic effects described by Grant[38] in 1900, except that he found hypersthene, and did not find tourmaline. Clements[39] notes similar features, but observed also the presence of hypersthene and biotite. Zapffe[40] found that the greenstones in the Gunflint Lake district contained a large amount of cordierite where they had been metamorphosed by the gabbro. He also found abundant hypersthene, and smaller amounts of biotite, chlorite, anthophyllite, etc. His average mineral composition of metamorphosed greenstones shows 50.65 per cent. of cordierite and 33.60 per cent. of hypersthene. No such rock was found on Gabimichigami Lake which could possibly be interpreted as a metamorphosed greenstone. A cordierite-hypersthene rock was found, however, which corresponds very closely to his description, but it is clearly a part of the Gunflint iron formation.

LOWER HURONIAN SEDIMENTS.

The metamorphism of the Lower Huronian sediments by the gabbro extends to a distance of a half-mile or more from the northern border of the main gabbro mass and consists principally in a recrystallization of the rocks and the production of biotite and sometimes garnet, together with the introduction of considerable amounts of blue tourmaline.

[38] Grant, U. S., "Contact Metamorphism of a Basic Igneous Rock," *Bull. Geol. Soc. Amer.*, Vol. 11, p. 511, 1900.

[39] Clements, J. M., "The Vermilion Iron-bearing District, Minnesota," Mono. 45, U. S. Geol. Survey, pp. 161 and 418, 1903.

[40] Zapffe, Carl, "Effects of a Basic Igneous Intrusion on a Lake Superior Iron-bearing Formation," ECON. GEOL., Vol. 7, p. 147, 1912.

The most far-reaching effect of the main gabbro mass upon the Lower Huronian sediments and to a less extent upon those of Upper Huronian age has been the introduction of tourmaline. Nearly every section of the slates and graywackes from the west and northwest sides of the lake contains a few crystals of bright blue tourmaline. It was found as much as a mile from the nearest gabbro. Northeast of the lake it occurs abundantly in the slates half a mile from the gabbro. The tourmaline occurs in long slender crystals or groups of radiating crystals, or in allotriomorphic grains. In one section it formed slender veinlets running nearly across the section.

Along the northeast shore of the lake, and nearer to the gabbro, the rocks contain flakes of brown biotite, which becomes more abundant in the neighborhood of the gabbro. Recrystallization has taken place and the clastic structure is lacking. The rocks consist of a fine mosaic of quartz and albite, in which lie myriads of tiny actinolite needles and biotite flakes. Some of the coarse-grained phases contain green hornblende and pale green diopside. Along the northeast shore near the portage to Paul Lake large poikiloblasts of garnet have been produced. Sometimes the rock consists almost entirely of garnet, but that mineral usually is present in the form of irregular poikiloblasts enclosing rounded grains of quartz and feldspar, and flakes of mica or grains of tourmaline. The garnet is pale pink in thin section, and is probably a "common garnet" containing a mixture of the grossularite, almandite, and andradite molecules.

The metamorphism of the slates in the Gabimichigami area differs from that previously described in that both garnet and tourmaline have been developed, in addition to mica, pyroxene, and amphiboles. The mode of occurrence of the garnet suggests that it has been formed by the recrystallization of constituents already present in the rock, under the influence of the high temperatures existing in the vicinity of the gabbro at the time of its intrusion. The tourmaline appears to have a different origin. Since it occurs in narrow veinlets of microscopic size, and in larger veinlets, there can be little doubt that it is a pneumatolytic product contributed by the gabbro.

UPPER HURONIAN SEDIMENTS.

Animikie Quartzite.—The Animikie quartzite is very thoroughly metamorphosed wherever it has been found in the vicinity of Gabimichigami Lake. It is such a rock as might be produced by the recrystallization of an arkose or a feldspathic quartzite. The abundance of calcite in some phases of the metamorphic rock suggests that the arkose or quartzite may have had a calcareous cement. Recrystallization of impurities accounts for the presence of cordierite, biotite and small amounts of actinolite, hornblende, diopside and hypersthene; and the accessories zircon, titanite, magnetite and apatite are those which are commonly found in quartzites. Blue tourmaline occurs in many sections of the quartzite, and, as in the case of the Lower Huronian sediments, it probably is a pneumatolytic product contributed directly by the gabbro.

Gunflint Iron-Bearing Formation.—A study of thin sections gives a qualitative idea of the composition of the iron-formation in its metamorphosed condition, and the kind of changes which must have taken place in order to produce such a rock from a ferruginous sediment. The relative importance of the different metamorphic processes, especially the processes of recrystallization of materials preëxisting in the rock, and of transfer of material from the intrusive gabbro to the intruded sediment, cannot be accurately determined until beds or bands are found which can be traced without doubt as to identification from the unmetamorphosed or slightly metamorphosed condition of the original sediment to the thoroughly metamorphosed condition of the contact rock. This is not possible for the rock at Gabimichigami Lake, for there it is everywhere thoroughly metamorphosed.

Clements[41] has described ferruginous cherts and iron-bearing carbonates from the Gunflint Lake region which he believes represent the original or slightly metamorphosed sediments from which the highly metamorphosed rocks in the vicinity of the gabbro were derived, but he does not record any quantitative

[41] Clements, J. M., "The Vermilion Iron-bearing District, Minnesota," Mono. 45, U. S. Geol. Survey, pp. 379–384, 1903.

study of the change. Concerning the rocks near Gabimichigami Lake, he states (p. 386): "The original rocks from which the iron-bearing rocks, . . . were derived, judging from analogy with the correlated iron-bearing formation of the Mesabi district, are supposed to have consisted largely of chert with a hydrous ferrous silicate, . . . with which is associated more or less iron, calcium, and magnesium carbonate. From rocks of this composition it is easy to see that the coarse-grained rocks, consisting of quartz, magnetite, olivine, hornblende, augite and hypersthene, might have been derived by simple recrystallization, without presuming any transfer of material from the gabbro."

Zapffe[42] also studied the iron formation near Gunflint Lake, and also concluded that the metamorphism took place without any appreciable transfer of material from the gabbro to the iron-formation.

A prominent feature of the iron formation where studied by Zapffe is the presence of pyrrhotite, both in the iron formation and the sills intruding it. A twelve-foot layer consisting of seven feet of iron formation and five feet of gabbro in two sills averages 14 per cent. of pyrrhotite, and one slide contained 35 per cent. He concludes (p. 165): "that the iron-bearing formation was originally rich in pyrite, and that due to regional metamorphism, heat supplied by the intrusives changed the pyrite present to pyrrhotite; sulphur fumes rose, and in a small measure perhaps combined with some of the ferrous iron available higher up in the series and thus accounts for the presence of the small amount of the pyrrhotite in the contact phase of the intrusive mass above, though the heat of the mass itself no doubt also prevented to some extent the formation of pyrite."

Again (p. 164), he states: "The various facies of the unmetamorphosed gabbro described by Winchell contain only a minute amount of pyrite, and in the calculation of the chemical composition of the average mass the sulphur content was a negligible amount. . . . In the Lake Superior region the iron formation

[42] Zapffe, Carl, "Effects of a Basic Igneous Intrusion on a Lake Superior Iron-bearing Formation," ECON. GEOL., Vol. 7, pp. 145–178, 1912.

rocks, such as the ferrous carbonates, are known to be pyritic, and in fact this mineral is so abundant in places that the rock is essentially a mass of pyrite with minor amounts of iron carbonate. It is easier to conceive the pyrite to be original in an iron formation of an aqueo-igneous type, as the Lake Superior iron formations prevailingly are, than to be abundant in the gabbroid rocks only at a place, as in this case, where this igneous mass is intrusive into or lies upon an iron formation."

It has been stated elsewhere (p. 371) that the gabbro does frequently contain sulphides at points far from any known iron formation and that these sulphides are of magmatic origin..

Zapffe says further (p. 165): "Undoubtedly the Archean greenstones below were metamorphosed at the same time as the Gunflint iron-bearing formation, but these fail to show any pyrite in the parts studied. Had sulphur been contributed by the gabbroid rocks, then these metamorphosed greenstones ought to show a sulphur content." On the west side of Gabimichigami Lake, however, the metamorphosed Archean greenstones do sometimes contain pyrrhotite, and associated with it is chalcopyrite. Pyrrhotite and chalcopyrite were found together in the gabbro at four places and in the gabbro-contact rocks at four others.

The constant association of chalcopyrite with the pyrrhotite is pretty good evidence that the latter was derived from some other source than that of recrystallized pyrite of sedimentary origin, especially since the chalcopyrite is frequently as abundant or more abundant than the pyrrhotite. The further association of pentlandite with these two in the quartzite as well as in the gabbro, in the vicinity of Gabimichigami Lake, makes any theory other than that postulating the derivation of the sulphides from the gabbro magma untenable. Furthermore, the wide distribution of pyrrhotite and chalcopyrite associated together in the gabbro and its contact rocks shows that the gabbro magma was competent to furnish enough sulphur for all of the sulphides that have ever been described from its vicinity. When one considers the immense size of the Duluth laccolith, as compared with

that of the Sudbury mass which has produced such quantities of sulphides, one wonders rather that larger deposits have not been found.

So far as the present evidence shows, the introduction of sulphides and of tourmaline has been the only contribution from the gabbro to the metamorphosed rocks. There is nothing to indicate that the presence in them of such peculiar minerals as olivine, hypersthene, fayalite, etc., and the unusual associations of olivine and quartz, etc., are due to any process except that of recrystallization of a rock which already contained the elements necessary for their production. This recrystallization took place under mass static conditions at the high temperature existing in the vicinity of a large intrusive igneous rock.

ECONOMIC FEATURES.

Iron Ores.—Some portions of the Gunflint formation consist very largely of magnetite, and attempts have been made to mine the deposits for their iron content. The principal effort of this sort was made at Paulson's Mine, about three miles west of Gunflint Lake, but the project was found to be unprofitable and was abandoned many years ago.

No magnetite masses of any size were observed in the Gunflint iron formation on Gabimichigami Lake, and none have ever been reported. It is quite unlikely that any commercial deposits or iron ore will ever be derived from this source.

Copper and Nickel Sulphides.—Nickel ores have been reported from the Duluth gabbro, but apparently the actual mode of occurrence has never been described. Winchell and Grant state[43] that "nickel ore is found in small amount in the gabbro, and many important finds of this ore have been reported, but as yet none of them have been substantiated." They elsewhere[44] give an analysis of a titaniferous magnetite in which 0.41 per cent. of nickel was reported. Clements states[45] that "a great deal of

[43] Final Report, etc., Vol. 4, p. 344.
[44] *Ib.*, Vol. 5, p. 496.
[45] Mono. 45, p. 420, etc.

money has been spent in exploring for nickel ore, which has been reported as occurring in the titaniferous magnetites in the gabbro," and refers to the above analysis quoted from Winchell's report.

The writer found small amounts of chalcopyrite and pyrrhotite in the gabbro at many points, and on examining polished surfaces of these sulphides under the microscope found that the nickel-iron sulphide pentlandite (FeNiS) is usually associated with them. The sulphides also occur in the contact-metamorphosed rocks along the northern border of the gabbro. Occasionally small masses consisting largely of sulphides occur in these rocks. The largest mass of this nature seen by the writer was found on the west side of the small island in Gabimichigami Lake which is crossed by the line between T. 64 N. and T. 65 N. The mass lies in a metamorphosed quartzite about 25 feet from its contact with the gabbro, which also contains the same sulphides in small grains. The mass is about a foot wide and was exposed as a narrow band for a distance of three or four feet. It consists of a crumbling, granular aggregate of rusty material in which may be seen many plates of a gray mineral with metallic luster. The freshest material that could be obtained was badly weathered and veined with limonite. In addition to the gray metallic mineral just mentioned, smaller amounts of pyrrhotite, bright yellow chalcopyrite, magnetite and some dark silicates can be recognized microscopically.

In thin section the silicates are seen to make up a very small part of the mass. They consist of augite, olivine and plagioclase, with a few tiny flakes of colorless or brownish anthophyllite which are alteration products of the augite and olivine. The silicates lie in rounded masses surrounded by sulphides and magnetite. Olivine grains are nearly always surrounded by a rim of augite and some of the magnetite grains are small and rounded, and likewise are surrounded by rims of augite. However, most of the magnetite, which is very abundant, lies in rounded masses which surround and embay the silicates. The sulphides also lie between and sometimes surround the rounded

grains of silicates. The appearance in thin section is very much like that of the lean ore from Sudbury described and figured by Tolman and Rogers.[46]

Specimens of the rock and of the sulphide-bearing gabbro from the same place, were polished and studied under the microscope. The following opaque minerals were recognized: Pyrrhotite, chalcopyrite, magnetite, pentlandite, chalmersite (?) and an unknown grayish white sulphide. The first four minerals were readily determined. The fifth occurs only in very small masses on which it is difficult to apply chemical reagents without overlapping adjacent minerals; but the color, hardness and chemical reactions as far as they could be determined correspond with those properties of chalmersite, as recorded by Murdoch.[47] The properties of the sixth mineral do not correspond with any of the minerals described by Murdoch, and its identity could not be established. Its properties as determined on polished surfaces under the microscope are as follows:

Color, white, with pyrrhotite grayish white, with chalcopyrite creamy white.

Hardness, 3.5–4.5, about equal to pyrrhotite.

Surface, rough. The mineral has a very perfect cleavage in one direction, and is so brittle that it is very difficult to obtain on it a smooth polish. Its surface consists of alternate ridges and grooves parallel to the cleavage.

Microchemical tests, (1) HNO_3 dil. Fumes tarnish brown; the mineral becomes brown and effervesces slowly with evolution of H_2S. Tarnish readily rubs off. (2) HNO_3 conc. Tarnishes brown, effervesces rapidly with evolution of H_2S, etches and blackens. (3) KCN. Negative. (4) HCl dil. Acid becomes bright yellowish-green but does not attack mineral or tarnish it. (5) HCl conc. Same. (6) Ac. Reg. Effervesces slowly and tarnishes brown. Tarnish rubs off. (7) $FeCl_3$. Negative.

[46] Tolman, C. F., and Rogers, A. F., "A Study of the Magmatic Sulfid Ores," Leland Stanford Junior University publications, University series, p. 30 and Plate 2, Fig. 12, 1916.

[47] Murdoch, Joseph, "Microscopical Determination of the Opaque Minerals," New York, 1916.

(8) HCl hot. Like HCl dil. (9) NH_4OH conc. Slowly tarnishes light brown, rubs off easily.

These properties correspond most nearly to those of polydymite, Ni_4S_5, but that mineral is not attacked by NH_4OH, while the unknown mineral is. Moreover, the unknown mineral cannot be a nickel or copper mineral, since the rock contains only 0.22 per cent. of copper and 0.12 per cent. of nickel, and there is sufficient chalcopyrite and pentlandite present to account for all of these, while the unknown mineral is the more abundant of the three minerals.

In all of the sections studied there was a definite order of crystallization, as follows: (1) Silicates, (2) magnetite, (3) chalmersite, (4) pyrrhotite, (5) unknown sulphide, (6) chalcopyrite and pentlandite.

Much of the magnetite surrounds or cuts through the silicates and is probably younger. Relations such as those figured by Tolman and Rogers[48] are common.

The chalmersite (?) occurs only in very small amount and was not found in direct contact with magnetite, but it is definitely older than pyrrhotite. It is regarded as younger than and has replaced pyrrhotite. The replacement begins around the borders of the pyrrhotite grains or along cracks. It penetrates the pyrrhotite in sharp blades or slender veinlets extending at right angles to the direction of the crack along which replacement starts (Pl. XVI., *c* and *d*), and continues in most cases until only a small core of pyrrhotite remains.

The chalcopyrite and pentlandite occur together in irregular masses which are younger than any of the other minerals, cutting through them in narrow veinlets (Pl. XIV., *d*) or enclosing angular fragments which have not been replaced.

The relation between the chalcopyrite and pentlandite is not so clear. The two are intimately associated, and although small masses of chalcopyrite occur without any accompanying pentlandite, the latter was found nowhere except in intimate association with chalcopyrite. The two minerals penetrate each other

[48] *Op. cit.*, Plate VII., Fig. 34.

in long, sharp blades, or lie in narrow parallel bands with perfectly straight, sharp contacts. Probably the two were deposited at about the same time.

This small sulphide mass is evidently genetically connected with the gabbro. It contains the same silicates and the same sulphides which occur in the gabbro nearby, and the order of crystallization of these minerals is the same. It contains very little plagioclase, however, but has an abundance of minerals which are characteristic of the later phases of crystallization of the gabbro. It probably represents a small offshoot of the gabbro, intruded at a late period in the crystallization of the main mass.

This small deposit has many characteristics in common with the magmatic sulphide deposits, which, according to Tolman and Rogers,[49] have been introduced at a late magmatic stage as a result of mineralizers. Thus:

1. It is associated with a subsilicic igneous intrusive.
2. It contains most of the ore minerals classed as characteristic of magmatic deposits.
3. Pyrite is absent.
4. The ore minerals were formed at a late magmatic stage by a partial replacement of the silicates.
5. There is a definite order of formation of the ore minerals which is characteristic of magmatic deposits of this type.

[49] Tolman, C. F., Jr., and Rogers, A. F., "A Study of the Magmatic Sulfid Ores," Leland Stanford Junior Univ. Pub., Univ. series, 1916. Pp. 7 and 70.

COPPER SULPHIDES IN SYENITE AND PEGMATITE DIKES.

D. H. McLaughlin.

An occurrence of chalcopyrite and bornite in dikes of syenite and syenite pegmatite which may be added to the list of deposits of the so-called magmatic sulphides, was encountered in the course of brief studies in the Boundary District in 1916.[1] These few notes concerning the deposit are presented as a slight contribution to the lively and interesting discussions constantly centered on sulphides in magmatic association.

The deposit mentioned lies on the slopes of the La Fleur Mountain, a few miles north of Danville in Ferry County, Washington. The sulphides occur in dikes of apparently unaltered syenite and syenite pegmatite, and to a minor extent in the wall rock. The sulphides in the dikes are later than the normal rock minerals and were probably formed in the period following their crystallization—the period for which the term pneumotectic[2] has been recently proposed—while the sulphides in the wall rock occur in associations which indicate that pneumatolytic or hydrothermal conditions prevailed during their deposition. The most important ores as exposed at present are those in the dikes and therefore according to the common practice the deposit would be classified as magmatic, but for exact designation the term pneumotectic is preferable to emphasize the place occupied by the sulphides in the sequence characteristic of ores of this sort and to avoid popular misconceptions often attached to the older term.

The ores on La Fleur Mt. have not been previously described. The only information available concerning the general geologic relations is to be found in the report of the Canadian Geological

[1] In connection with the Secondary Enrichment Investigation.

[2] L. C. Graton and D. H. McLaughlin, "Further Remarks on Ores of Engles, Cal.," Econ. Geol., Vol. XIII., pp. 81–99, 1918.

Survey[3] which deal with the Boundary District immediately to the north. The nearest mines are the Lone Star, a small property of the British Columbia Copper Company, about three miles distance, and the larger mines of the Granby Company at Phœnix, about ten miles or so across the boundary. The mineralization in these deposits, however, is distinctly different in character from the ores under discussion.

The claims on La Fleur Mt. have been developed only to a very slight extent by a few shallow shafts or short adits. A little ore has been mined and shipped, but no noteworthy work has been done. The greater number of the claims are the property of Mr. G. S. Trombley, to whom the writer is indebted for many courtesies.

ROCK FORMATIONS.

The older rocks of the mountain form a series of various sediments of which limestone beds and some altered porphyries are prominent members. From the mapping on the Canadian side of the line, it is possible that the sedimentary rocks may be members of the Attwood series—argillites, quartzites and limestones—stated to be of Carboniferous(?) age. A diorite porphyry, now altered in places to a somewhat schistose rock containing abundant biotite and shreddy amphibole, is associated with the sediments, but neither its exact relations to them nor the form of its bodies could be detected.

The older rocks of the mountain are intruded by an irregular mass of gabbro. The rock varies from dark varieties in which hornblende is prominent, to lighter types in which feldspar predominates. In the commonest form, the rock possesses a medium to fine grained texture, and is composed chiefly of acid labradorite (Ab_5An_5), and colorless to pale green augite. Hornblende is usually present, apparently formed in part at the ex-

[3] R. W. Brock, Summary reports of the Director of the Geological Survey of Canada for 1901 and 1902.

R. A. Daly, "Geology of the North American Cordillera at the 49th Parallel," Part I., p. 377, 1913.

O. E. LeRoy, "The Geology of the Phœnix Mining District," Memoir 21, G. S. C., 1912.

pense of the pyroxene. In places the rock becomes of dioritic character. Small seams of pegmatitic material, nearly always feldspathic with little or no quartz, are common throughout the rock. They are usually less than one inch in thickness.

The gabbro is cut by dikes of coarse syenite, averaging about four feet in width, but occasionally much wider. In places, the rock becomes distinctly pegmatitic, with the orthoclase developed as crystals two or three inches long. A sub-parallel orientation of the feldspar prisms is usually prominent. It suggests a flow structure. The chief mineral of the syenite or syenite pegmatite is orthoclase. Under the microscope, albite is found to be common also, usually in smaller grains around the margins of the coarser orthoclase, and to a slight extent in microperthite intergrowths. Muscovite is the only other mineral prominent in the syenite. It occurs as medium-grained flakes of slightly greenish tinge when seen with the unaided eye. The mica is closely associated with the albite and is usually a constituent of the zone of finer grain surrounding the coarse orthoclase crystals. Both the albite and muscovite are in part later than the orthoclase. Other constituents are of little quantitative importance. Titanite in sharp crystals is not uncommon, and there is a little apatite. Where in contact with the altered porphyries of the older series, a little augite sometimes develops in the dike rock. Other modifications with respect to the wall rocks are closely related to the processes of the mineralization and will be described in that connection. The dikes are in a north-south zone and may be traced about a mile, although no single dike is continuous for that distance.

The latest igneous rock is a gray diorite porphyry, which forms a broad dike cutting all other formations. It is fresh and unmineralized, and in striking contrast to the older and more or less altered rocks of the mountain.

MINERALIZATION.

Ores in the Syenite Dikes.—The mineralization is closely associated with the syenite or syenite-pegmatite dikes. The sul-

phides, bornite and chalcopyrite, are most abundant in the dikes themselves, but where the dikes cut the gabbro, the sulphides penetrate the wall-rock along fine seams or occur disseminated through it to a slight extent. The mineralization in the dikes however is not continuous and it is only locally that the sulphides are sufficiently abundant to constitute an ore.

The ore-minerals corrode the orthoclase, albite and muscovite, but with the exception of an albite rim which often is present between the ore-minerals and the orthoclase, there is no other important alteration of the rock-minerals. A little fine-grained muscovite or sericite is sometimes developed in the albite, and later calcite replaces the feldspars to a slight degree, but the general absence of alteration products which usually accompany sulphide mineralization is an outstanding feature.

Mineralization in the Wall-rocks.—Where the dikes cut the limestone members of the sedimentary series, a garnet rock is formed from the limestone and is composed chiefly of andradite, albite and calcite, with a little diopside, titanite and apatite. This rock contains numerous small cavities between the crystals of its constituents, and a scattering of chalcopyrite grains. Garnet is also abundant in one part of the syenite dike itself on one of the claims on the east end of the mountain, and is probably to be attributed to the influence of limestone on the magma. The garnet is poikilitic with albite, and probably crystallized later than the feldspars. The mica in this part of the dike is chiefly biotite, and the colorless muscovite, abundant elsewhere, is in small flakes and quite subordinate.

Where the mineralization has penetrated the gabbro, also, there is pronounced rock-alteration. There is a notable increase in hornblende near the dikes, and also along the small seams of feldspathic pegmatitic material which cut the rock. The sequence of minerals is well shown in one thin section which includes a portion of the edge of one of these stringers. The pegmatitic material is largely orthoclase and albite, in microperthitic relations for the most part; near the margins garnet is slightly developed. In the rock nearest the seam, hornblende is most

abundant. In places it possesses a rim of deeper green than the heart of the grain. Farther into the rock, pyroxene (colorless augite) becomes of greater importance and is the chief femic constituent. Epidote and chlorite are abundant as replacements of hornblende, pyroxene and the feldspars. The older plagioclase of the rock contains abundant sericite and calcite. Apatite and titanite are somewhat more abundant in the rock than is usually the case. The chief opaque mineral in this particular slide is magnetite, which is later than the pyroxene and feldspars, and in part at least, later than the hornblende, for all the preceding minerals are clearly corroded by it. It frequently includes small apatite grains.

Ore-Minerals.—The ore-minerals are chiefly chalcopyrite and bornite. The former is slightly more abundant. Magnetite is largely confined to the gabbro; it was not observed in ores from the syenite. The ore-minerals in the dikes are later than the rock-minerals, as has been stated, although probably not very much later, for there are so few alteration products associated with them, they having merely corroded rather than transformed or altered the rock minerals. In the gabbro, they are probably contemporaneous with the alteration products, epidote and chlorite.

The chalcopyrite and bornite are usually in close association, and in part probably of contemporaneous origin. The contacts between the two minerals, as shown on the polished surface, are smooth and even, with few irregularities such as tongues or veinlets which would definitely show sequence. In many cases, their relations to each other would be little altered if the two minerals were interchanged. This relation has been termed the *mutual boundary,* and is believed to be particularly characteristic between minerals of the primary sequence. There is a little evidence, however, of corrosion of the chalcopyrite by the bornite in some places, and it is probable that conditions favoring the formation of bornite continued for a short time after the deposition of chalcopyrite had ceased, which resulted in a slight replacement of the chalcopyrite by the bornite.

Magnetite, and a small amount of specularite are probably earlier than the sulphides, but their relations could not be determined with final satisfaction in this deposit.

A little sphalerite, galena, and tetrahedrite were observed as small specks on the polished surfaces in the midst of the more abundant sulphides.

OXIDATION AND ENRICHMENT.

The deposits occur in a mountainous region of mature topography and possess no noticeable gossan, a fact which may be attributed to the present vigorous erosion and preceding glacial scour to which they have been subjected. A small amount of limonite and malachite occur, but the sulphides outcrop directly at the surface in a fairly fresh condition. A small amount of chalcocite, covellite and chalcopyrite occur in the bornite, and are undoubtedly to be attributed to the processes of secondary enrichment, but so far as their total copper content is concerned, they are of little importance.

The chalcocite is in fine veinlets or rims associated with the bornite. It follows the easy channel-ways afforded by the contacts of bornite and the gangue or rock minerals, or seeks out grain boundaries, seams, or other obvious lines of attack. Covellite is for the most part the first stage of the alteration of chalcocite to malachite and usually occupies an intermediate position between the two minerals. It develops directly from bornite, however, to some extent. The veinlets of chalcocite and covellite penetrate the primary chalcopyrite, but as the latter is clearly more resistant to alteration, they do not develop as easily in it as in the bornite.

The bornite in the neighborhood of the chalcocite and covellite veinlets commonly contains a small amount of chalcopyrite, which is closely related in origin to the secondary sulphides. The chalcopyrite in this association develops as plates in the bornite, appearing oriented parallel to three or rarely four crystallographic directions, which on the polished surface yield the reticulate pattern known as *the lattice structure*. In some

grains of bornite, the plates of secondary chalcopyrite are so thin and so finely spaced that they are scarcely visible under the highest available magnifications, and it is justifiable to assume that the peculiar yellow color of certain areas of bornite in the same vicinity is due to submicroscopic chalcopyrite of this sort.

DISCUSSION.

The syenite and syenite pegmatite dikes are possibly late products of the magma from which the gabbro crystallized. The small seams of pegmatitic material which are common in the gabbro, and which would ordinarily be accepted as its pegmatitic phases, are closely related mineralogically to the syenite, and are probably of the same origin. The greater alteration and more abundant mineralization of the gabbro along the ore-bearing portions of the syenite dikes than is the case where other rocks are encountered might be interpreted as an indication that the gabbro was still heated at the time of the intrusion of the syenite, and in a receptive state to react with the vapors given off.

The coarse grain of the syenite, its variable texture and numerous miarolitic cavities may be regarded as strong evidence that gases played an important rôle both in the formation of the differentiate and in the determination of the character of the crystallization. The sulphides are believed from their close association with the unaltered (though corroded) rock minerals to be late products of the crystallization of the magma, but formed at a time when strictly magmatic or orthotectic[4] conditions had been appreciably modified and to some extent controlled by the increasing concentration of gaseous constituents or so-called mineralizers. It is to the products of such conditions—and among them is believed to be included most of the so-called magmatic copper sulphides—that the term pneumotectic has been applied.

There is an absence of positive mineralogic evidence of strictly pneumatolytic action in the syenite, but, in the adjoining limestone, the garnets with some sulphides and the hornblende along

[4] L. C. Graton and D. H. McLaughlin, *loc. cit.*

the walls in the gabbro are probably products of gaseous reactions most properly described by that term. Hydrothermal products are almost lacking in the dikes, but in the gabbro away from the immediate vicinity of the walls, epidote, sericite and chlorite become prominent, and indicate a gradual fading in intensity of mineralization with distance from the syenite. Sulphides in small amounts occur with these minerals and indicate a continuance of their formation into the period of hydrothermal conditions. The closing phase of the mineralization is marked by development of calcite.

The alteration of the ores by surface agencies is slight, but affords a clear example of bornite altering to chalcocite covellite, and with the development of secondary chalcopyrite in fine lattice structure in parts of the bornite protected from direct attack by the oxidizing agencies.

Distinct resemblances are seen, both in the primary and in the secondary processes and results, to the deposits at Engels, California, and to other bornite occurrences which it is the writer's intention to describe at a later time.

QUICK METHOD OF RECONNAISSANCE MAPPING.

M. L. FULLER.

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INTRODUCTION.

The system of topographic and geologic reconnaissance mapping described in the following pages is one used with great success by F. G. Clapp and the writer in oil explorations in China in 1913, 1914 and 1915. No new processes are involved, the system being a combination of old methods, with certain modifications tending to simplify the work and increase its rapidity without materially lessening its accuracy.

By its application the geologists were enabled to sketch the roads, villages, drainage, topography and, in most areas, the geology from horseback as they proceeded, without stopping their horses for either observations or note taking.

Under the methods usually followed, the mapping of ten to

twelve miles per day is a common average where the work is done with the detail characterizing the work in China, while fifteen miles is an exceptionally good day's work. With the introduction of the various time-saving factors of the method under discussion, however, the distance covered is limited only by the number of miles a horse can walk per day, usually twenty-five to thirty miles, while the accuracy is of a high order for this class of work.

In actual practice, *the distance covered in a given time was doubled and the cost of the exploration of a given territory cut in half by attention to details.* (See paragraphs on "Time Saved by Method" and "Effect on Cost" in closing portion of paper.)

At first sight it may seem almost superfluous to call attention to such simple and apparently almost axiomatic methods, but the writer's experience has shown him that the mapping systems used in explorations by even some of the most experienced geologists fail by a large margin to reach the efficiency of the method here described.

OUTLINE OF METHOD.

The salient features of the system may be briefly summarized as follows:

1. A mounted guide or leader to head the party, select the route, and set a steady, even pace.

2. A geologist, following immediately behind the leader, whose horse his own follows closely, making guidance unnecessary and leaving hands free for compass and barometric observations and note taking.

3. The taking of compass bearings to the *nearest five degrees, while in motion.*

4. The direct plotting of courses by *standard coördinates while in motion.*

5. The determination of distances *by time while in motion.*

6. The sketching of culture and topography *while in motion.*

7. The determination and plotting of geology, usually in motion, but stopping when necessary.

8. The inking in of map and notes, and the elaboration of the latter in the evenings.

DETAILS OF METHOD.

Pace-Making.—The mounted guide and pace-maker is an indispensable factor to the proper working of the system. The geologist cannot head the party or attend to the driving of his horse without great loss of time. If the reins are not in hand the horse is continually distracted and invariably wanders from a straight line on the slightest provocation.

All this, of course, interrupts the geologist's observations and note-taking, using up a large amount of time and tending to introduce numerous errors of omission as well as interfering with distance determinations based on time.

The actual time loss where the geologist attempts to drive without a leader has been found, in the case of most horses, to amount to about a fifth of the number of hours spent in the saddle, or some two hours a day. This, on an average, is equivalent to about six miles.

With a leader, most of this loss is obviated, as the geologist's horse commonly learns to follow the pace-maker in a few hours, making it possible to leave the reins hanging from the pommel with the geologist's hands free to attend solely to his scientific work.

Compass-Bearings.—Compass-bearings are taken directly with a Brunton (direct reading without mirror) to the ***nearest five degrees.*** If midway between two five-degree marks, that mark is taken which is opposite that taken on the last preceding split-course.

The reading to five degrees introduces a possible error of a little over two degrees or about 200 feet to a mile on long straight courses, but in actual practice several courses are usually taken in a distance of a mile and the errors tend to neutralize one another. As a matter of fact, the closure of work is usually exceedingly close.

Plotting of Courses.—Plotting is done by standard coördinates

on cross-ruled note-books with five squares to an inch. Angles are plotted as read—to the nearest five degrees, errors neutralizing one another as in the case of the readings themselves.

The coördinates used are as follows:

Degrees.	Short Coördinate (Squares).	Long Coördinate (Squares).
5	¼	3
10	½	3
15	½	2
20	1	3
25	1	2½
30	1	2
35	1	1½
40	1	1¼
45	1	1

All plotting is done while the horse is in motion, the first course starting from a known or assumed point, with the succeeding course starting from the first turning-point, and so on. The courses are sketched lightly with the pencil in indeterminate lengths, the parts beyond the successive turning points being erased as soon as the new courses are plotted.

Most of the coördinates soon become fixed in mind, but to avoid loss of time in case of lapses of memory a table of coördinates should always be pasted on the inside of the front cover of the note-book, ready for instant reference.

Determination of Distances.—The determination of distances is *by time.* This method proved remarkably successful, doing away with the old nerve-racking system of counting paces, which not only prevented the geologist from taking notes while counting but also made it impossible to make anything but the most casual observations. Moreover, serious errors due to loss of count are almost sure to creep in at times under the old method. Under the present method, on the contrary, the geologist is not burdened with counting, but is absolutely free between turning points to observe topography, geology and culture, and to sketch and describe the same.

The distance travelled by one's horse in a given time is determined for each horse before mapping is begun on the time basis.

In China this was done by comparison with a cyclometer affixed to a bicycle wheel pushed by a coolie, but it may be easily done anywhere by direct comparison in advance with a few measured lines under varying conditions of topography.

The writer used two cyclometer wheels at the start. These were found to vary about 5 per cent. from each other. The pace of the horse, after the first few days, was found to vary less from the mean than did the wheels themselves, and the latter were soon discarded.

The average time per mile naturally varied considerably according to the freshness of the animals, character of the ground, topography, etc., although the range was less than might be expected. In the morning when most horses were sluggish, it took about two minutes more to the mile than it did an hour later, when they were limbered up. Toward night they occasionally lagged again, but if a village was in sight their "homing instinct" kept them at a quick gait, sometimes even above the normal. We soon learned to allow for the varying moods of the animals, as well as the character of the ground.

The following table summarizes the average speeds under varying conditions.

SPEED OF HORSES' WALK UNDER VARYING CONDITIONS.

(Minutes per Mile.)

	Horse Fresh.	Horse Sluggish.
Low to moderate grades.		
Good surfaces	18	20
Poor surfaces—		
Sand (deep)	20	22
Mud (sticky)	21	23
Stony	21	23
Steep grades.		
Good surfaces	20	22
Poor surfaces	23	24

Occasionally, special conditions, such as the deep sticky muds of overflowed lands, the shifting sand dunes of the deserts, and the boulder-covered slopes of the mountains, necessitated special allowances for short distances, but there was seldom any diffi-

culty in estimating the rate of movement with a good degree of accuracy.

In crossing rivers by ferries the width may be estimated by the eye, which soon becomes trained to judge distances with accuracy, or in case of wider streams, by triangulation.

In climbing zigzag trails up cliffs of loess or rock, with individual courses perhaps not more than a rod or two in length, it is commonly more accurate to take the general bearing of the trail as a whole from above or below and estimate the distance.

Crooked paths through thick jungle present particularly trying conditions, and general estimates of directions and distances may have to be relied upon, with such checks as may be had by triangulation on conspicuous points. The errors are usually found to be unexpectedly small, however.

Plotting of Distances.—In China, distances were measured in li (pronounced lee) which are almost exactly one third of a mile. One half li to each square of the note-book was found the most convenient scale for that country. This was equivalent to 6 squares or 1⅓ inches per mile. If a mile scale is used 4, 5, 8 or 10 squares will be found more convenient, according to the amount of detail to be plotted.

In plotting in the note-book those courses which cross the squares diagonally, the length equivalent to the recorded time is commonly estimated. Little allowance has to be made in crossing a square where the angle made with the ruled lines is 15 degrees or less, but for greater angles, especially from 30 to 45 degrees, considerable allowance must be made. With the squares at hand for a guide, and remembering the diagonal of a square is 1.4 times its side, the allowance may be made with fair accuracy by estimation. A scale cut on the side of the pencil may help, but a scale that must be hunted for each time is to be avoided.

Experience has shown that with most men there is a slight but constant tendency to underestimate the distances in plotting, and one's personal equation in this respect should be determined by re-plotting the traverse to an exact scale early in the work. It is seldom necessary to do this more than once or twice, however.

Tables giving the time equivalents of a square in the notebook for each bearing, the most common rate of travel, and the usual scale of mapping should be prepared and placed on the inside front cover.

Elevations.—Elevations along the immediate line of travel are determined by aneroid barometers, and are necessarily more or less approximate, although it is possible to largely eliminate errors due to diurnal variations by taking 6 A.M. readings as a standard and allowing for a depression of 20 to 30 feet from 6 A.M. to 8 A.M., followed by a slow rise of about 60 feet up to noon, then a more rapid rise of perhaps 100 feet additional to 4.30 P.M., with a decline of 20 feet to 6 P.M. The afternoon maximum in China was usually about 120 feet above the morning reading at the same point. The diurnal curve should be determined as nearly as possible for each day and locality.

The error of elevation at any given point on normal days is seldom in excess of 50 feet and is believed to be usually under 25 feet where both diurnal and instrumental corrections are applied. Without the latter correction, however, the errors will often be much greater since individual barometers often show constant differences from a standard mercury barometer amounting to several hundred and, in cases of high altitudes, even as much as 1,000 feet.

Elevations of objects off the trail are usually estimated, and are at the best only approximate, except where angles are taken in addition. A surprising accuracy in estimation is soon acquired, however.

Geology.—In reconnaissance work few stops are usually necessary for geological observations where the rock types are readily recognized and the structure simple. A little practice makes it possible to estimate dips to a single degree, where not in excess of 5 or 10 degrees, by the eye alone, and to the nearest 5 degrees or closer for the higher dips, which is usually sufficiently accurate for reconnaissance work. With dips under 1 degree measurements are usually made from the difference in elevation of bed in travelling a fixed distance.

In all important areas the reconnaissance should be followed by plane-table or other detailed work, as was the case in China, but this does not form a part of the method under discussion.

Representation of Culture.—The trails and roads are designated by dotted or double lines as on the U. S. Topographic Sheets, all angles being indicated *without generalization.* Cities, villages, ponds, canals, telegraph lines, and, in China, temples, pagodas, watch towers and the Great Wall are all indicated. Subsequent use of the maps thus prepared has shown that they can be followed even across featureless plains with as much ease as the latest government topographic maps and far more readily than the older ones.

Inking-in Notes.—The notes, taken while the horse is in motion, are crude in appearance and often much abbreviated. If allowed to stand twenty-four hours, the geologist who took them is often at a loss in interpreting them. Immediate inking and elaboration is therefore essential. The latter includes barometric corrections, explanations, interpretations, etc. Colored inks and crayons should be used freely. The original pencil lines are erased after inking and checking, but before coloring. The time usually required is from one and one half to two hours daily. All conveniences, in the shape of folding table, chairs, lamps, drawing utensils, etc., should be carried. The saving in the geologist's time far more than counterbalances the cost of purchase and transportation.

APPLICATION OF METHOD.

The field procedure in the method under consideration is as follows:

1. Take position immediately behind guide or pace-maker who heads party.
2. Locate starting point on page in such position that as much of the route as possible may be plotted before turning the leaf.
3. Take compass bearing to nearest 5 degrees.
4. Plot compass course by a line of indefinite length by the coördinate method, using a fixed side of the note-book as north.
5. Read watch and barometer and set down time and elevation against starting point.

6. Start, keeping horse at a steady walk behind pace-maker.

7. While moving on first course, sketch in (1) culture, including houses, canals, intersecting roads, trails, etc., (2) topography, by hachures or approximate contours, (3) geology, including character of rocks and dips.

8. At turn of road or trail read the watch immediately, without stopping, and set off the distance covered on the time basis on the line representing the first compass course. Mark the time against this turning point, together with the barometric elevation of the latter.

9. Take new compass bearing and plot while in motion as before.

10. Repeat operations in sequence described.

11. When it is necessary to stop to make geological observations, collect specimens or fossils, take photographs, or for other purposes, indicate the stopping point in the same manner as the turning point, making sure that the time of stopping is set down. On starting again, set down the starting time, and continue on old or new course as before. Be sure to note any change of barometer during stop.

PROFILE WORK.

In some areas of stratified rocks where key beds are present it becomes desirable to run barometric profiles showing outcrops and structures along the line of traverse.

It is possible to carry such profiles simultaneously with the mapping, using the opposite page and tying map and profile to one another by common "tie points" or "identification points," but the mapping, if properly done, requires the closest attention and is in itself, in most cases, a sufficient tax on the geologist's ability. If profiles are to be carried for a long distance two geologists to a party will be found desirable. When one man attempts to carry both traverse and profile an undue strain is put upon him, unless he takes the work very leisurely, in which case speed is greatly reduced.

MINOR DETAILS.

There are a number of minor details which it may seem at first thought superfluous to mention, but which the writer's experience has shown to be so frequently disregarded by even the more experienced men that he believes the more important of them should be enumerated and emphasized. (*a*) Rubber bands should be used to hold down the leaves and keep the place. (*b*) Tables of standard courses, coördinates, and time and distance equivalents should be written or pasted on the inside of the front cover (back cover being strapped to leaves by rubber bands). (*c*) Sandpaper for sharpening pencil should be pasted on the outer edge of the back cover where it can be reached by turning up the edges of the leaves without disturbing the rubber bands which hold the latter down. (*d*) The note-book case should be of heavy leather, *without flap,* sufficiently stiff to hold itself constantly open, and large enough to allow the note-book to be dropped into it readily. It should be strapped to the front of the saddle so as to be instantly accessible. In many year's experience the writer has never known of a note-book falling from an open case. When raining the case may be worn on belt beneath coat. (*e*) Instruments should be carried in large loose pockets in preference to cases carried on the belt, as the flaps to this type of case interfere with quick handling of the instruments.

Wrist watches should invariably be used in work of the nature described.

Pencils should be carried so as to be quickly accessible, in special pockets if necessary.

ACCURACY OF METHOD.

Closure.—The closure is in most cases surprisingly close. A day's work ending at the starting point commonly closes within a small fraction of a mile. A week's circuit of perhaps 150 miles often closes as accurately as that of a single day, and is rarely as much as a mile out. A four to eight week's circuit of from 500 to 1,000 miles usually closes within two or three miles, or with an error of only one third of 1 per cent.

Distances.—The closures show that errors of distance, if any, are likely to be very constant. There was no close check in China, in the absence of latitude and longitude determinations at any of the outlying points on a circuit, and although the existing maps suggested a possible error of several miles at points 200 to 500 miles from a base, the distances as computed from time agreed very closely with measured distances whenever an opportunity for checking presented itself. Thus in covering the highway from the end of the railway at Mienchih in Honan to Shanchou, a distance of about 40 miles, the distance by timing, as determined by the writer, agreed within less than half a mile with the cyclometer measurements made by Prof. G. D. Louderback. This was closer than two cyclometers would register when run side by side.

Comparative Accuracy.—While absolute accuracy is not claimed, the errors, as indicated in the foregoing paragraphs, are comparatively small, and, if distributed carefully in the final plotting, will become almost inappreciable. An error of 3 miles, which is about the maximum, distributed over a route 500 miles in length, will be negligible locally.

In fact, if plotted on a scale of one or two inches to a mile, it will be difficult to distinguish a route run and plotted by the method here described from one based on stadia or plane-table work and plotted with protractor and scale. Certainly the gain in accuracy, if it has any practical value (which it seldom has), is in no way commensurate with the additional cost involved in instrumental work or even in closer compass readings and protractor plotting.

The writer, however, specifically limits his claims of advantage to reconnaissance work or to mapping on a comparatively small scale.

TIME SAVED BY METHOD.

The following estimates of time saved are based on observations made for the special purpose at various times.

In all, six hours per day were saved and made available for

constructive work, and the speed increased from a rate of 10 or 12 miles a day under inefficient (yet common) methods to 25 to 30 miles per day under the method described.

TIME SAVED.

How Saved.	Hours per Day.
Use of pace-maker	2
Reading of compass to nearest 5 degrees instead of to 1 degree	½
Plotting courses by coördinate method	½
Calculating of distances by time instead of counting	½
Plotting notes while in motion	2
Attention to minor details	½

EFFECT ON COST.

The reduction of the cost of work by the application of the method under discussion is fully 50 per cent. In a party costing $75 a day this is equivalent to a saving of $37.50 per day, or of $50 per day in a party with operating cost of $100 per day. With the prevailing rate of remuneration of consulting geologists of the better grade, the savings indicated are by no means abnormal.

DUTY OF THE GEOLOGIST.

The prevailing salaries of geological experts, as just indicated, is high, and the companies employing them are entitled to a high grade of service. It is not sufficient to do accurate work. It should be done expeditiously and economically as well. The geologist who does not make an earnest study of field methods and seriously endeavor to work out the most rapid and economical system applicable to the particular work in hand, consistent with accuracy, is not doing his full duty.

APPLICATION OF FOOT WORK.

The method described in the foregoing pages is adaptable to work on foot, but necessarily with a considerable reduction of speed. Distances can be measured by timing, as on horseback, compass bearings may be taken to the nearest five degrees and plotted by standard coördinates, but it is necessary to stop to read compass and barometer and to sketch route, culture, topography and geology.

The theoretical reduction of speed (see table under "Time

Saved by Method") should be about two hours per day, equivalent to about six miles, but in actual practice a man's walk does not average as fast as that of a horse and there are many more causes of delay. The reduction is therefore more than the table suggests, fifteen miles per day being, in fact, a very fair length of traverse, under ordinary conditions, when working on foot.

APPLICATION TO WORK WITH WAGON.

The method is applicable to work with a buggy or wagon in many instances, although in cases the iron about the vehicle interferes with compass readings, necessitating getting out and stepping some paces away in order to get correct bearings. The necessity for this may be determined by experiment with the wagon headed in various directions. A uniform speed is essential if time is to be used for measuring distances, while the rate of movement must be fairly slow if notes are to be sketched while in motion. A driver is practically essential.

APPLICATION TO AUTOMOBILE WORK.

The method has been used in the United States in rough reconnaissance work from an automobile, but its application necessitates leaving the machine and going a rod or two away (more if the engine and generator are running) to secure reliable compass bearings. Distances are measured by the odometer indicator of the speedometer to the nearest tenth, with estimates to half tenths. Notes can seldom be plotted while in motion.

The results are satisfactory only in special cases, as where there are long straight stretches of road and where there is little to sketch. Owing to the necessity of frequent stops, the speed is little more than when a horse is used, while notes are not only less complete but less accurate. It is very difficult to make satisfactory observations from an automobile, especially when the geologist is driving. In general, they should be used only in the roughest kind of mapping, when little depends on its accuracy. A Ford or other machine without a self-starter is almost useless in the type of work described.

DALLAS, TEXAS.

NOTE BOOK FORM AND SYMBOLS FOR PETROLEUM GEOLOGISTS.

E. G. Woodruff.

Geological field work in the oil regions of the United States has now developed along well-recognized lines, therefore a standard set of forms and symbols should be adopted. This brief paper is intended to suggest a basis for such unity of action for the benefit of those now at work and the more rapid acquisition of a good working knowledge by those entering the industry.

The Texas Oil Company has adopted standard methods for its various divisions. For detailed work the general planetable methods are used. Elevations are determined and checked, outcrops located, etc. To properly record the alidade readings and to avoid error in planetable work and provide a check in case of error there is used the printed form of traverse notebook sheet shown below (note book size 5″ × 8″):

STATION		Distance	Rod Reading	ANGLES			Difference in Elevation	+ or −	ELEVATION		Station Number	Table or Rod	REMARKS
From	To			Inclination	Horizontal	Difference			Table	Rod			

If observations are correctly made and recorded this form presents a quickly checked and easily reviewed form of permanent notes and also offers checks against errors in note recording in the field.

Columns 1, 2 and 3 are self-explanatory. Column 4 (Rod

Reading) is used when the sight is sufficiently near the horizontal that the middle stadia wire falls on the rod when the tele-

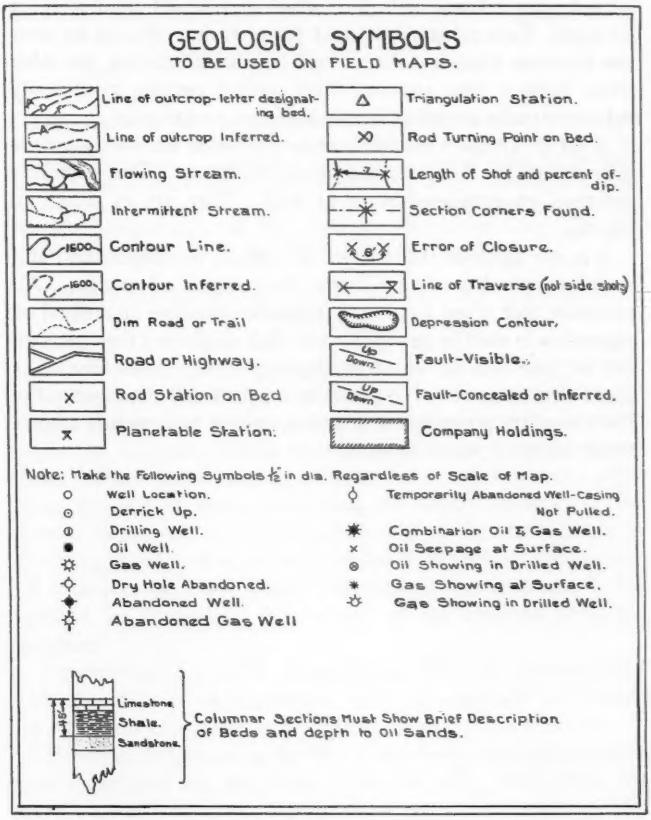

FIG. 29.

scope is horizontal; when the rod is too far above or below the telescope to be read the columns under "Angles" can be used for recording angular readings. The column under "Difference

in Elevation" is for the computed number of feet of difference in elevation. The next column is to indicate whether the observed point is lower or higher, which may be indicated by + or — sign. Two columns are used for elevation, the one to show the elevation when it is determined from a rod station, the other when from a table station. This method permits more ready reference to the elevation figures and thus avoids error.

A set of symbols has been devised to show accurately and to differentiate the data recorded on the planetable. These symbols are used on completed maps as well. They are as shown in Fig. 29.

It is not supposed that this set of symbols is complete and universally applicable. It is felt that they possess advantages. All recognize that when a common symbolic language or method of expression is used by geologists and their employers then geology can be, and will be, more intelligently used. Therefore, it is urged that some set of symbols be adopted and used generally. The above are presented as a basis on which to construct a commonly accepted set of symbols.

DISCUSSION

This department has been established by the editors in order to afford to those interested in questions relating to economic geology an opportunity for informal discussion. Contributions are cordially invited either in the form of discussion of more formal papers appearing in earlier numbers or bearing upon matters not previously treated. Letters should be directed to the Editor, Sheffield Scientific School of Yale University, New Haven, Conn. The full name of the author should be attached to all communications.

THE HALOGEN SALTS OF SILVER AT WONDER, NEVADA.

Sir: In your November, 1918, issue, Mr. J. A. Burgess made reply to an alternative hypothesis which I had suggested for the origin of the silver haloids found at Wonder, Nevada, in which reply Mr. Burgess strongly maintained that their formation was from surface waters, and called to his aid in support of his argument the law of mass action and the effects of erosion: the former to account for the inverted order of the precipitation of the halogen salts of silver, and the latter to account for the lack of a cerargyrite zone, which must necessarily, according to his method, be formed in the removal of the chlorine from the solution.

I cannot agree with Mr. Burgess that there are no unexplainable objections to his hypothesis, for if his argument is followed to its logical conclusion it leads to some extravagant results.

However, before going further, I would say that any explanation to account for the origin of an ore-body, must, from the very nature of the case, be but of a hypothetical nature. The natural forces which were operative during the formation of an ore deposit presents a problem with so many unknown factors that what may, to the investigator, appear to be a logical explanation for the genesis of the ore deposit under examination, may, through facts brought out later, or through a better under-

standing of the mass of geological facts now, or later available, weaken, if not entirely disprove that which appeared to be a scientific fact. Therefore, I consider any explanation, including my own, for the origin of an ore deposit as of but a tentative nature, subject to revision to conform with later presented facts.

In amplification of the idea for the magmatic source of the chlorine, bromine and iodine which went to form the haloid silver salts in question, I would say that a search of the geological literature will well bear out the idea that the earth, as the reservoir from which all of the elements found at its surface were derived, is competent to have furnished directly the halogens found in these deposits. That they were supplied from a magmatic source would also reasonably account for the various proportions and combinations in which the chlorine, bromine and iodine are found, which appear to be never quite the same in any two deposits. Were the halogen silver compounds formed by downward percolating solutions containing the halogens in about the proportions to each other as they occur in sea-water, more regularity as regards the proportions of the various haloids found would be expected for this type of deposit.

Also, the fact that the odor of bromine[1] is noticeable in the stopes rich in the bromo-chlorides would strengthen the suggestion of gases from a magmatic source,[2] for, it would be possible for uncombined gases to be occluded in the halogen silver salts, while with downward percolating solutions containing the halogens as soluble compounds, any excess of the soluble halogen compounds over that required for the precipitation of the silver would be carried away by the solution into the general ground-water circulation still as a soluble halogen compound.

The geological literature which has come under my observation has been barren of any mention of bromine and iodine to

[1] Burgess, J. A., "The Halogen Salts of Silver at Wonder, Nevada," ECON. GEOL., Vol. XII., No. 7, 1917, p. 593.

[2] Clarke, F. W., "The Data of Geochemistry," Bull. 616, U. S. Geol. Surv., 1916, p. 335. In footnote 5, Clarke cites H. Becquerel and H. Moissan (*Bull. Soc. chim.*, 3d series, Vol. 5, 1891, p. 154) as authority for the presence of free fluorine in fluorite.

which the writer attributed a direct magmatic source, though such is not the case regarding magmatic chlorine, for numerous mention of such is made. As the association of the halogens at Wonder is such that they were undoubtedly all derived from the same source, the probable source of one would be the probable source of all.

Clark,[3] in his chapter on volcanic gases and sublimates gives many references to chlorine and chlorine-bearing compounds as being exhaled by volcanos and extruded molten lava.

A number of chlorine-bearing minerals are found in igneous rocks,[4] and are also frequently found in contact metamorphic zones and deposits. Scapolite, sodalite and chlorapatite being the most common of these chlorine-bearing rock-forming minerals of magmatic derivation.

Emmons and Calkins[5] determined scapolite as a primary mineral in the batholiths of the Philipsburg Quadrangle. The chlorine locked up in the rocks here is mentioned as being "measurable in cubic miles."

It would appear that there is no dearth of magmatic chlorine.

As Mr. Burgess builds his argument around the law of mass action to account for the precipitation of the chlorine as cerargyrite, the more readily soluble silver salt, ahead of the less soluble bromine and iodine silver compounds, and employs the effects of erosion to account for the non-existence of the so formed cerargyrite zone, his hypothesis then, should stand or fall on its being followed to its logical conclusion.

Chlorine and bromine are in proportion to each other in seawater[6] as 55.292 is to 0.188, or about 294 parts of chlorine to

[3] *Op. cit.*, pp. 260–290.

[4] Clarke, F. W., *op. cit.*, pp. 419–475. Also in the *Min. and Sci. Press*, June 22, 1918, p. 857 (extract from Prof. Paper No. 96, U. S. Geol. Surv., by Arthur C. Spencer). Joseph B. Umpleby, in Prof. Paper No. 97, U. S. Geol. Survey., 1917, p. 54, cites Kemp and Gunther (*A. I. M. E. Trans.*, Vol. 38, 1908, pp. 269–296) as authority for the occurrence of scapolite in the Mackay Region, Idaho.

[5] Emmons, W. H., and Calkins, Frank C., "Geology and Ore Deposits of the Philipsburg Quadrangle, Montana," Prof. Paper No. 78, U. S. Geol. Surv., 1913, pp. 122, 128 and 159.

[6] Clarke, F. W., *op. cit.*, p. 123.

one part of bromine. The chlorine and bromine in the silver haloids at Wonder are in the ratio of one to one,[7] thus leaving 293 parts of chlorine for the cerargyrite zone which is supposed to have been eroded. The haloid salts of silver have been found to a depth of 1,300 feet, and in this depth one part of the 294 parts of the chlorine has been used. Without entering into refinements of the calculations, if but one part of the 294 parts of chlorine was used in 1,300 feet, at the same rate, to use the remaining 293 parts of chlorine would require an upward extension of the vein 1,300 times 293, or 380,900 feet, or a trifle over 74 miles. In vertical distance the amount of erosion would be about 71.5 miles.

I shall leave the reader to apply such corrections as may, in his judgment, seem most suitable for the unknown factors covered by the above figures.

JACOB W. YOUNG.

MARYSVALE, UTAH.

THE BENDIGO QUARTZ VEINS.

Sir:—The discussions of Professors Alan M. Bateman and S. Taber on the "Bendigo Quartz Veins" on pp. 222–223, 538–545, of Volume XIII., are interesting and require further comment. In the preparation of my paper for ECONOMIC GEOLOGY, pp. 100–111, Volume XIII., my aim was to demonstrate briefly that replacement of slate occurs in the Bendigo quartz reefs, and secondly that the replacement is probably a very important part of the explanation of the location of the gold shoots. I did not aim to produce a complete account of the quartz reefs which had already been attempted in a tentative manner in my first report on the goldfield.[1] At the time these papers were written I was not acquainted with the important researches of Professor Taber, but the application of these researches to the Bendigo quartz veins has since been described in a later report published

[7] Burgess, J. A., *op. cit.*, p. 590.

[1] Stillwell, F. L., "The Factors Influencing Gold Deposition in the Bendigo Goldfield," Bulletin No. 4, Advisory Council of Sci. and Ind. Aust., Melbourne, 1917.

in Melbourne last year.[2] I am indebted to Professor Taber for a more complete picture of the formation of the reefs. Apart from this the restricted nature of the paper and the fact that neither writer had read Bulletin No. 4 would account for part of the discussion. The main conclusions are unaffected.

It was not my intention to set forth any estimate of the relative importance of replacement as a process of reef formation at Bendigo, except in "leg reefs" which occur in the sheared limbs of the anticlines. A "leg reef," as I have used the term, is distinct from the tapering leg of a saddle. The leg of a saddle reef may merge into a leg reef, but the latter is not necessarily continuous with a saddle reef at all. The more important leg reefs have been mined in east-dipping beds and are known locally as "eastern bedded reefs." Such a term is undesirable because similar reefs occur on the western limbs of the anticlines, while saddle and trough reefs are aso bedded reefs. Some of the difficulties raised in the discussions are due to a misconception of a leg reef. Only in leg reefs and occasional saddle reefs do we find the carbonaceous laminæ extending across the full width of the quartz. The presence of these laminæ in the white quartz is interpreted as evidence of replacement, and while this evidence is fairly general in the saddle reefs, only in isolated cases is it abundant, and in others it is almost absent.

It is only fair to state that the researches of Professor Taber have provided the demonstrations and the necessary proof of the theory that growing veins can enlarge themselves by pushing apart the enclosing walls. The theory was advocated by E. J. Dunn twenty-five years ago in his work on Bendigo, but references in text-books indicate that his evidence was insufficient to gain any general support for his conception.[3] Further an essential adjunct of Dunn's theory was the belief that the dark laminæ in the laminated quartz at Bendigo represented films of slate

[2] Stillwell, F. L., "The Factors Influencing Gold Deposition in the Bendigo Goldfield," Part II., Bulletin No. 8, Advisory Council of Sci. and Ind. Aust., Melbourne, 1918.

[3] Lindgren, W., "Mineral Deposits," p. 155. Beyschlag, Vogt and Krusch, "Ore Deposits," trans. by D. J. Truscott, p. 612.

detached from the wall rock. This adjunct has been used as a supporting argument by Taber[4] and in his subsequent discussion of my paper he has endeavored to substantiate it.

It has not been claimed that all laminated quartz is produced by one process. Still Taber's explanation of the laminæ of sericite in the quartz veins of the southern Appalachians is not without its difficulties. He speaks (p. 541) of thinner layers of quartz sericite schist, embedded in quartz veins, from which the quartz, in some cases *has been largely removed*. The removal of quartz during the development of a quartz vein surely involves the simultaneous deposition and solution of quartz, or the replacement of quartz by quartz—a difficult assumption when applied generally. It is an assumption not justified by the study of replaced sandstones at Bendigo. Here it is an unquestionable fact that a bed of sandstone, when traced along its strike, may gradually change into a quartz reef. The nature of the process seems to me to be a silicification of the matrix and an enlargement of the detrital quartz grains, followed by a recrystallization. Until the recrystallization occurs the residual particles are more or less evenly distributed and the color of the sandstone remains gray.

The statements of Dunn, quoted by Taber (p. 542) as requiring no comment, are not irreconcilable with my theory of the residual origin of the laminæ, except in so far as they record incorrect statements of fact and statements of theory. A vein, newly formed by replacement, is necessarily a porous body and if the replacement is confined to a fractured bed between two relatively non-replaceable beds, and if the supply of the mineral solution is more than sufficient to replace the fractured bed, the quartz reef will continue to grow and push apart the walls in the way demonstrated by Taber. A reef may in this way be laminated either on the footwall or on the hanging wall side, while the laminations are still replacement residues. The laminæ are not simple films of slate similar to the wall rock. Replace-

[4] Taber, S., "Mechanics of Vein Formation," *Trans. Amer. I. M. E.*, Bull. 140, p. 1208, 1918.

ment of slate and the formation of laminæ are not confined to veins that run parallel to the bedding and cleavage planes. Many instances have been observed in spurs where thin laminæ are parallel to the bedding planes of the adjoining rock, or parallel to the walls of the spur, or irregularly disposed. Not infrequently the residues are so dispersed that they are not visible to the naked eye and merely darken the quartz.

It is true that the laminæ are far more abundant in bedded veins than in spurs. Yet such is natural when one reflects that the mineral solutions travelling in the direction of the bedding planes along a shattered bed are able to enter along closely spaced cleavage and bedding planes and so acquire greater opportunity to replace the contiguous rock than when travelling through cross fractures.

The theory that the carbonaceous laminæ are replacement residues rests upon direct microscopical observations and it needs to be repeated that transverse section of the illustrated specimen of preserved brecciation (Plate V.) show laminæ.[5] The laminæ thus appear in areas where it is admitted that replacement occurs. The theory that the laminæ are films of slate ignores the following:

1. The mineral composition and structure of the laminæ are not simply those of the adjoining slate.

2. The frequent passage of a single dark lamina into fragments of ordinary slate with lobate outline, which again tail out along the course of the lamina.

3. The irregular and tortuous course of some laminæ. While the general trend of the laminæ may be parallel to the wall, the actual course in detail may be a series of S curves.

4. The presence of delicately frayed ends of groups of laminæ when these die out in areas of white quartz.

5. The reappearance in correct alignment of these groups of laminæ on the further side of the white quartz areas.

6. The presence of numerous laminæ, sometimes in branching networks, in a single crystal of quartz.

[5] See Plate IX., Bulletin No. 4, and Plate VIII., Bulletin No. 8.

7. The interlocking granular structure of the fine quartz crystals that mark the course of some laminæ in polarized light.

8. Quartz reefs resulting from the replacement of sandstones contain isolated and irregular laminæ, compared with reefs formed by the replacement of slates.

9. Occasionally dark threads similar to the reef laminæ are found in silicified sandstones.

10. The composition of the laminæ is much more closely related to the "reef casing" which occurs on the walls of a number of reefs than to normal slates. The "reef casing" is a hard, shiny graphitic slate-like material which consists of fragments of slate, micaceous particles and dark carbonaceous particles embedded in quartz.

The significance of these facts seem to me to preclude the "thin slate film" hypothesis as a general explanation of the laminated quartz in the Bendigo reefs Rather do they add weight to the hypothesis of "slaty residues."

FRANK L. STILLWELL.

BENDIGO, AUSTRALIA.

REVIEW

The Factors Influencing Gold Deposition in the Bendigo Goldfield. Part II., Bulletin 8, Commonwealth of Australia, Advisory Council of Science and Industry. By F. L. STILLWELL. 47 pages and 17 plates. Melbourne, 1918.

Part I of this investigation was published earlier as Bulletin 4 of the same series, and an epitome of it by the author has appeared in this Journal (Vol. 13, pp. 100–111, 1918). The present report gives the results of further research in the Bendigo goldfield, between August, 1917, and August, 1918, and discusses in detail some of the problems of gold deposition set forth in Bulletin 4.

The conclusions reached in Bulletin 4 are in general sustained and are reinforced by the new evidence since obtained. The reefs are regarded as having been formed in part by filling of open fissures, in part by replacement of slate and sandstone, and in part by making room for themselves by the force of crystallization. The gold has been localized in shoots, commonly at the intersection of the reefs and premineral faults. This localization would necessarily occur, it is believed, if the auriferous solutions had entered the growing reefs from faults that served as the main paths for the rising solutions. As the carbonaceous matter in the slates appears to have favored the precipitation of the gold, the solutions must have become progressively poorer in gold as they moved along the reefs from the points of entry. As long as carbonaceous matter remained unreplaced at or near these points of entry, gold would continue to be deposited here, and lessening quantities of gold would be precipitated as the solutions became increasingly depleted as they flowed along the reef. It is therefore vital to the proposed hypothesis to establish the premineral origin of the faults, and much of the bulletin consists of the presentation of the structural evidence for their premineral origin. Although the main faults antedate the deposition of the bulk of the quartz and gold, it is admitted that some later fracturing and deposition of quartz has taken place.

It is interesting to note that the hypothesis is advocated that the force of crystallization was an important factor in the growth of the veins, an idea previously advanced for these deposits by Dunn in 1896. This factor had not been considered in the earlier report, where some emphasis

was laid on the efficacy of the intrusive pressure of the ore-depositing solutions in opening the fissures. Evidently influenced by the important experimental work of Taber, the author now seeks to show that the force of crystallization has been highly effective in the genesis of the Bendigo gold veins. However, the fact that in some veins there are many large vugs, some of them two or more feet in diameter, cautions us against accepting this explanation unreservedly.

From the foreword that the Executive Committee of the Advisory Council has prefaced to the present report we learn that "resolutions expressing appreciation of Dr. Stillwell's work and requesting that it might be continued for a third year have been received by the Executive Committee of the Advisory Council from the Victorian Chamber of Mines, the Australasian Institute of Mining Engineers, and the Bendigo Branch of the Federated Mine Managers' Association of Victoria. The Executive Committee has agreed to continue the research on condition that the Bendigo mining companies contribute to the cost of future work on a pound for pound basis." It is evident on reading Dr. Stillwell's report that the appreciation of these practical organizations was inspired not alone by the practical results achieved, but also by the clarity and the admirable succinctness with which these practical results have been presented and the noteworthy promptness with which they have been made available.

ADOLPH KNOPF.

SCIENTIFIC NOTES AND NEWS[1]

L. C. GRATON has taken charge of the Copper Division of the Industrial Unit of the U. S. Bureau of Internal Revenue.

J. F. KEMP has been re-appointed professor of geology in Columbia University.

DR. J. MACKINTOSH BELL has resumed mining practice and has returned to Canada.

J. E. SPURR has resigned as Executive of War Minerals Investigations, Bureau of Mines, to take effect July 1. The War Minerals Investigations work will be terminated on that date.

MR. ELIOT BLACKWELDER has resigned his position as professor of geology at the University of Illinois. After September 1 his headquarters will be at Denver, and he will devote his time largely to geologic research, principally regarding the Rocky Mountains.

CHESTER A. HAMMILL has resigned from the Geological Department of the Roxana Petroleum Company in order to undertake independent investigations. He will be located in Dallas, Texas.

SCOTT TURNER has recently been appointed consulting engineer to the Mining Corporation of Canada, at Toronto, Canada.

RALPH ARNOLD has completed his government service and has resumed practice as consulting petroleum geologist and engineer with offices in Los Angeles and New York.

PAUL BILLINGSLEY who has been in the Army with the rank of captain, and attached to the office of the Chief of Staff in Washington, has been mustered out and has resumed his former connection with the Anaconda Copper Company, changing his location from Butte to Seattle.

[1] Geologists, mining engineers and others interested in applied geology are invited to keep the editor informed of new investigations of mining districts or scientific studies undertaken by them, together with such other scientific and personal items as may come to their notice.

H. W. KITSON is making a geological survey for the Iron Cap Copper Company at Copper Hill, Gila County, Arizona.

S. G. GARRETT is now with the Humble Oil Refining Company at Cisco, Tex.

ROBERT W. GIBSON, recently of Anaconda, Mont., is now on the geological staff of the Rocky Mountains Division of the Roxana Petroleum Company, of Oklahoma, Wyo.

JOSEPH E. POGUE, formerly associate professor of geology and mineralogy in Northwestern University, has terminated his duties as Assisting Director in Technical Matter, Bureau of Oil Conservation, Oil Division, U. S. Fuel Administration, and accepted the appointment of curator in the Division of Mineral Technology, U. S. National Museum.

J. JERVIS GARRARD has been elected president of the Geological Society of South Africa.

A. A. HASSAN has opened a consulting geological office at Fort Worth, Texas, and is temporarily located at the Westbrook Hotel.

JOHN T. FULLER has accepted a position with the American Bauxite Company, Bauxite, Ark.

ROBERT ANDERSON recently returned from Stockholm, Sweden, where he was representative of the War Trade Board and American delegate on the Inter-Allied Trade Committee. He is now at his home at Menlo Park, Cal.

HAROLD K. SHEARER is engaged in consulting geological work in association with A. C. Scott, at Dallas, Texas.

F. R. VAN CAMPEN has returned from Alaska, and is now at Seattle, Washington.

H. N. LAWRIE, after serving several years as chairman of the Oregon Bureau of Mines and Geology Commission, has assumed the post of chairman of the Division of Precious and Rare Metals of the American Mining Congress.

THE GEOLOGICAL SOCIETY OF AMERICA, Cordilleran Section, held its nineteenth annual meeting in conjunction with the Pacific Coast Branch of the Paleontological Society, and the Seismological Society of America, June 19–22, at Pasadena, Cal.

THE STANDARD OIL COMPANY is in readiness to start drilling at the site of its well No. 1 near Moclips, at the end of the Northern Pacific Railway's branch line, extending thirty miles north from Aberdeen.